

Convegno “ANALISI e ATTIVITA’ di MITIGAZIONE del DISSESTO IDROGEOLOGICO”

*Foggia, Martedì 6 Giugno 2017*



# INFRASTRUTTURE IDRICHE IN PENDII IN FRANA: il caso della frana Piscuolo in agro di Melfi (PZ)

Prof. Federica Cotecchia

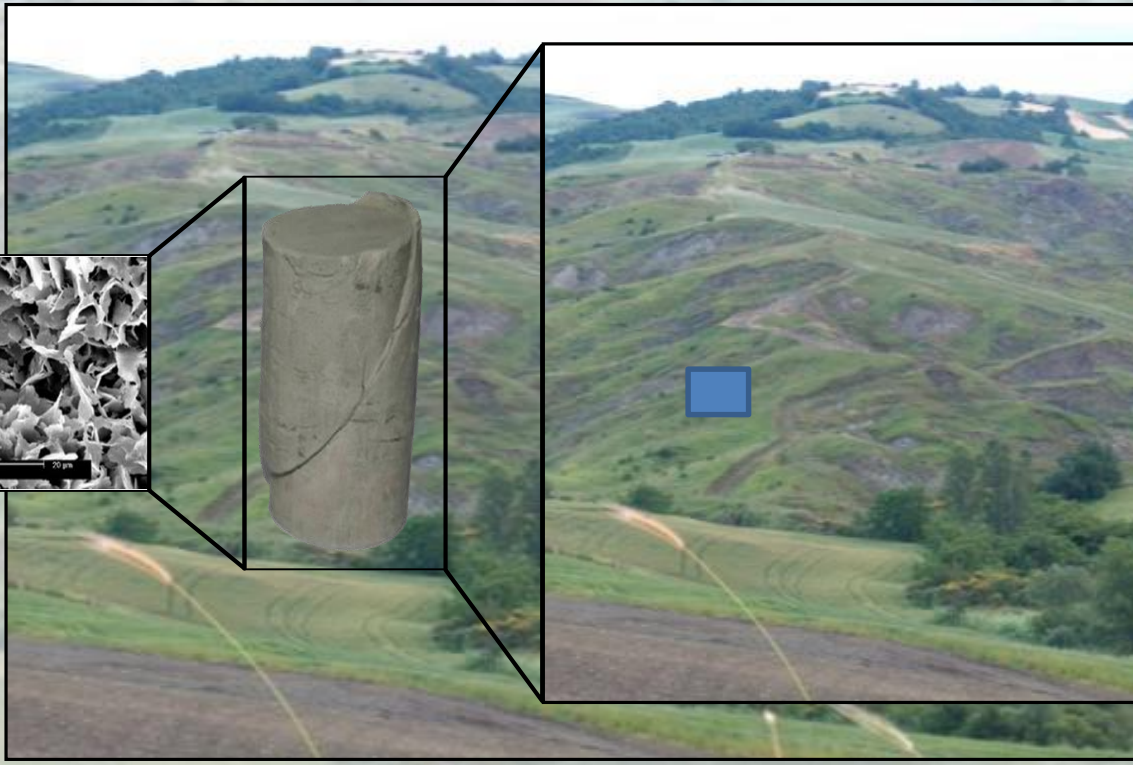
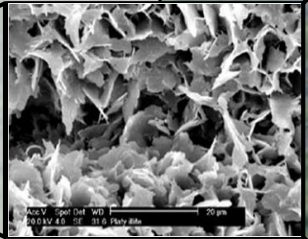
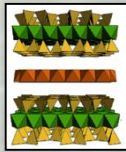


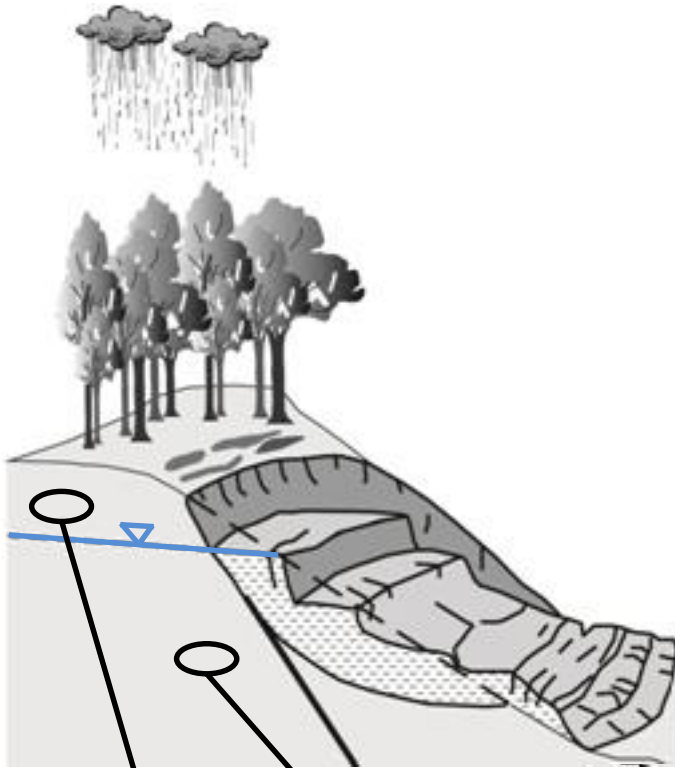
Francesca Santaloia\*\*, Osvaldo Bottiglieri\*, Giuseppe Pedone\*,  
Simona Guglielmi\*, Vito Tagarelli\*



1. L'approccio geo-meccanico nell'analisi dei meccanismi di frana
2. Il contesto geologico e idro-meccanico del versante Pisciole, prototipo nell'ambito del margine occidentale dell'Appennino Meridionale
3. I danni ricorrenti alla condotta Ofanto e alla strada statale SS106 Ofantina
4. La campagna geognostica, geofisica e geotecnica: assetto geo-meccanico del pendio
5. Rilievi di superficie e profondi: assetto geo-morfologico e cinematismo dei corpi di frana
6. Fattori predisponenti ed innescanti l'attività attuale della fenomenologia franosa
7. Modellazione numerica dell'interazione pendio-atmosfera e dell'attività di versanti del tipo Pisciole

# DIAGNOSI del meccanismo di frana





## FATTORI INTERNI

- Assetto geologico:  
*litologia, morfologia, strutture tettoniche, condizioni al contorno*
- Proprietà meccaniche:  
*parametri di resistenza, legge costitutiva e rigidezza*

Elasto-plasticità

$$\sigma'_{ij} \leftrightarrow \varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^p$$

- Proprietà idrauliche:  
*permeabilità, curva di ritenzione*

## FATTORI ESTERNI

- Agenti climatici:  
*pioggia, temperatura, irraggiamento, umidità relativa, vento*
- Agenti antropici:  
*carichi, scarichi, cambiamenti delle condizioni idrauliche al contorno*
- Azioni sismiche:  
*carichi e scarichi ciclici ad alta frequenza*
- Naturali evoluzioni morfologiche:  
*carichi, scarichi, weathering*

(Terzaghi, 1950)

### Totale saturazione

$$\sigma'_{ij} = \sigma_{ij} - u_w \delta_{ij}$$

### Parziale saturazione

$$\sigma'_{ij} = (\sigma_{ij} - u_a \delta_{ij}) + \chi(u_a - u_w) \delta_{ij}$$

(Cotecchia et al., 2014, 2015)

## EQUILIBRIO E CONGRUENZA

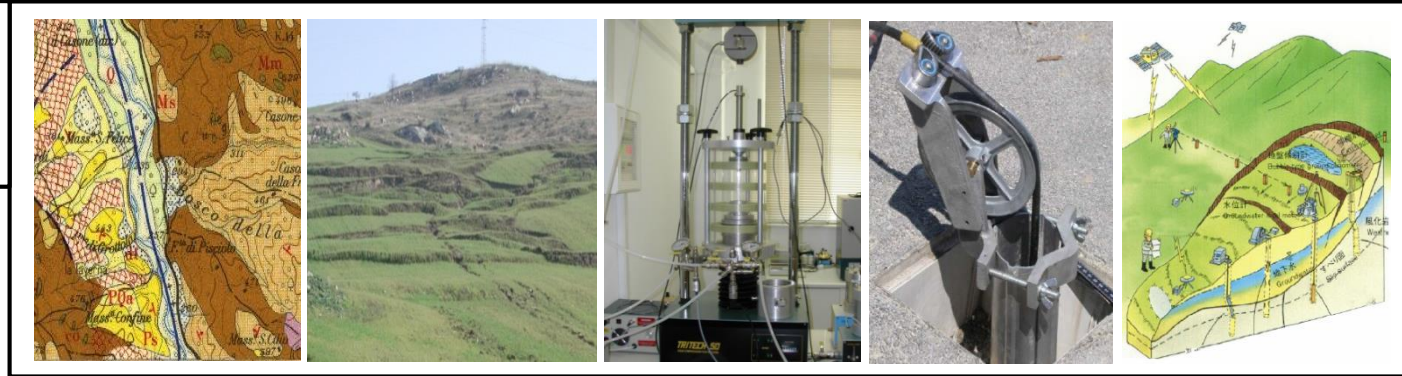
$$\left. \begin{aligned} \frac{\partial \sigma_{ij}}{\partial x_i} + \gamma \delta_{jz} = 0 \quad \frac{\partial^2 \varepsilon_{ij}}{\partial x_h \partial x_k} + \frac{\partial^2 \varepsilon_{hk}}{\partial x_i \partial x_j} = \frac{\partial^2 \varepsilon_{ih}}{\partial x_k \partial x_j} + \frac{\partial^2 \varepsilon_{kj}}{\partial x_i \partial x_h} \end{aligned} \right\}$$

## FILTRAZIONE TRANSITORIA

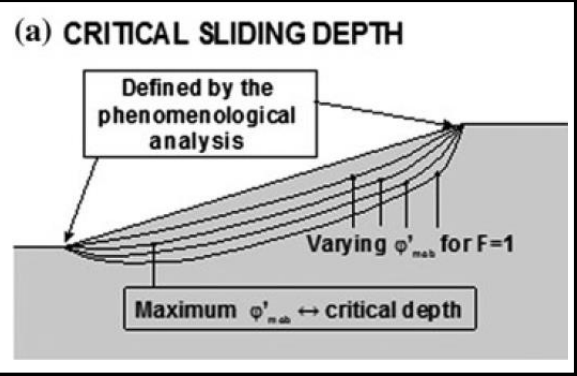
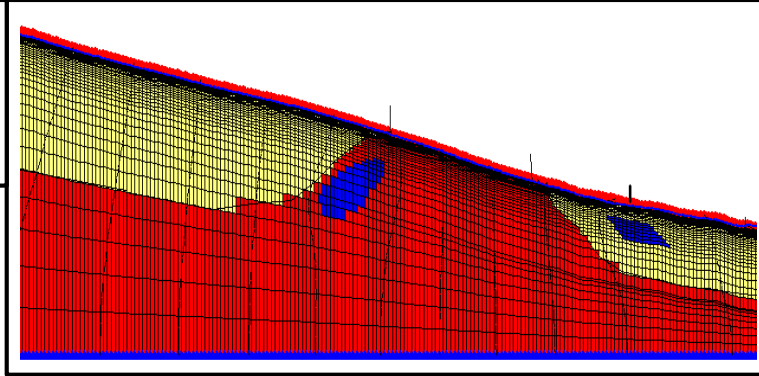
$$\frac{\partial}{\partial x_i} \left( \rho_w k_i \frac{\partial h}{\partial x_i} \right) = \frac{\partial}{\partial t} \left( \rho_w \frac{e S_r}{1 + e} \right)$$



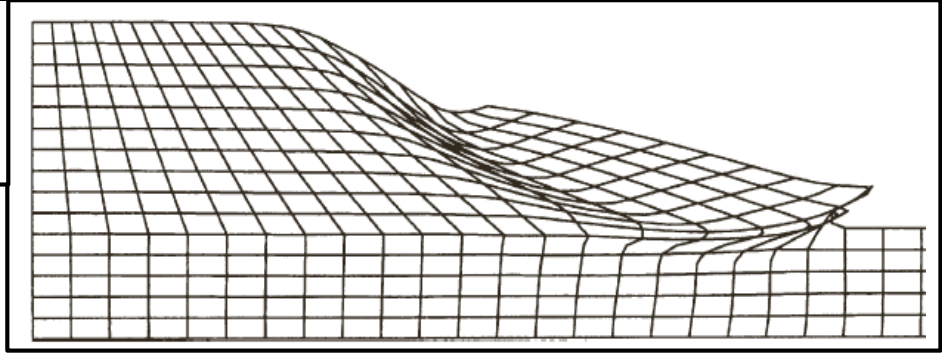
Analisi Fenomenologica  
I

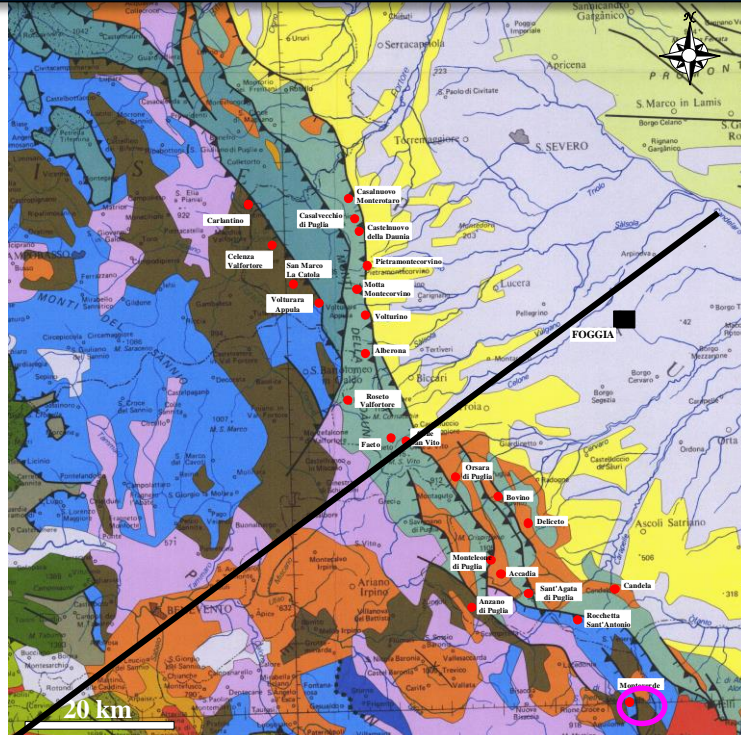
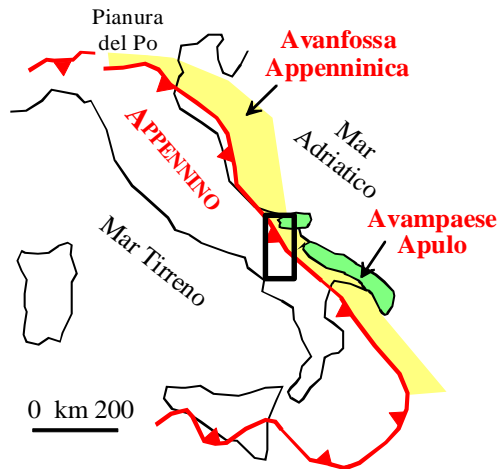


Analisi semplificate  
(all'Equilibrio limite)  
II



Modellazione numerica  
III





Successioni torbiditiche, depositi pelagici, e depositi di delta di fiume e di piattaforma



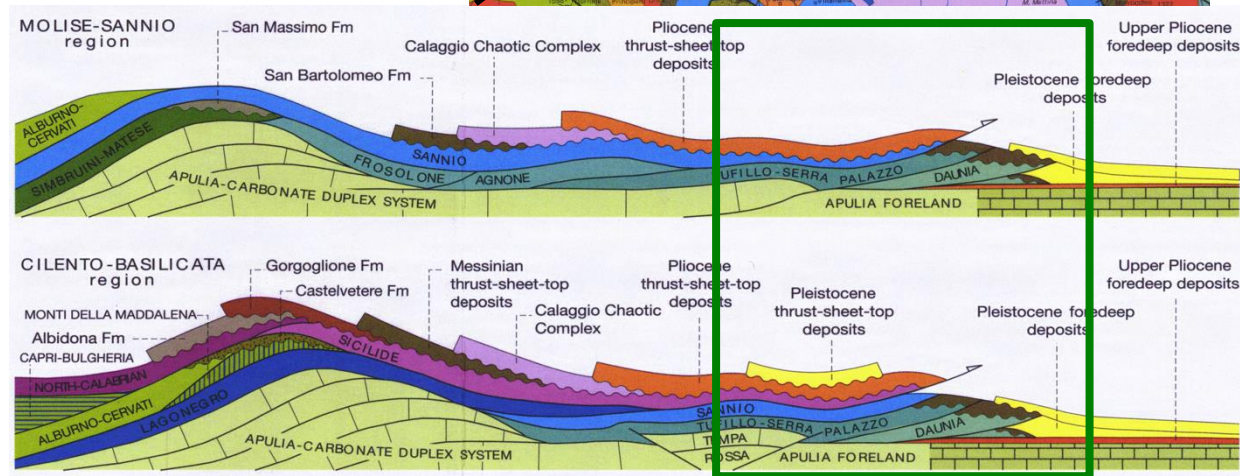
Marne di Toppo Capuana



Flysch di Faeto



Flysch Rosso



(Scadone e Patacca, 2008)



## Unità argillose



## Unità Rocciose

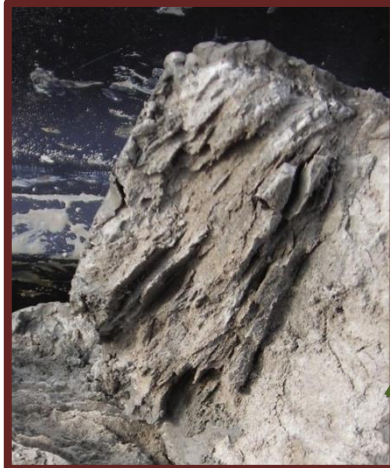


## Unità sabbioso- conglomeratiche

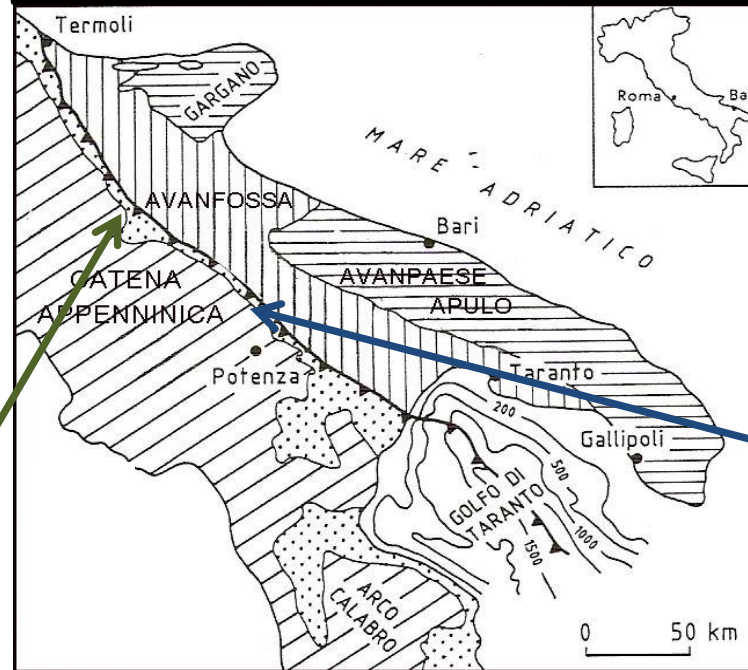
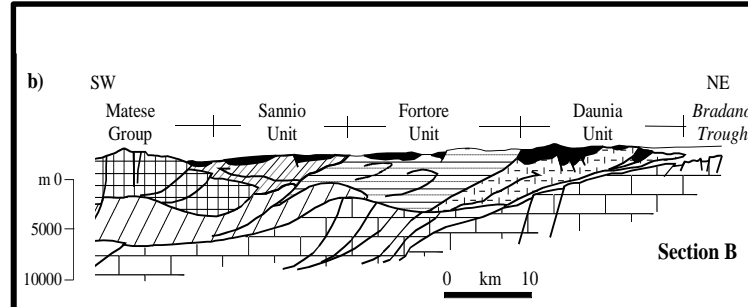




## Basse resistenze meccaniche delle argille fessurate



**Marne di Toppo Capuana**



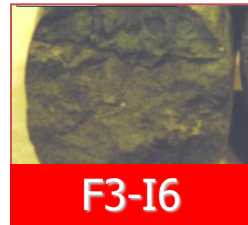
**Flysch Rosso**

(Vitone & Cotecchia, *Geotechnique* 2011)  
 (Vitone et al. *NAG*, 2013; *ACTA GEOT.* 2013)





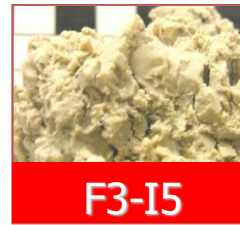
F1-I6



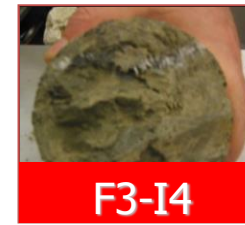
F3-I6



F3-I6



F3-I5



F3-I4

	TERRENO INTEGRO		NATURA DELLE DISCONTINUITÀ			ORIENTAZIONE DELLE DISCONTINUITÀ	GEOMETRIA DELLE DISCONTINUITÀ		
	Principale natura del sedimento <b>A</b>	Resistenza non drenata° <b>B</b>	Tipo <b>C</b>	Scabrezza* <b>D</b>	Stato <b>E</b>	<b>F</b>	Forma <sup>-</sup> <b>G</b>	Continuità <sup>-</sup> <b>H</b>	Intensità <sup>+</sup> <b>I</b>
1	Argilla	Argillite	Deposizionali	Molto scabre	Inalterate	Sinola 	Piane	Continue	Molto bassa: < 3 m <sup>2</sup> /m <sup>3</sup> - > 1 m <sup>3</sup>
2	Limo	Argilla consistente	Rilascio tensionale	Scabre	Poco alterate	Discontinuità 	Curve	Molte intersezioni	Bassa: 3÷10 m <sup>2</sup> /m <sup>3</sup> - 0.027÷1 m <sup>3</sup>
3	Argilla limosa	Argilla mediamente consistente	Indotte da azioni di taglio	Leggermente scabre	Molto alterate	Casuali	Piane e curve	Alcune intersezioni	Medio-bassa: 10÷30 m <sup>2</sup> /m <sup>3</sup> - 0.001÷0.027 m <sup>3</sup>
4	Limo argilloso	Argilla soffice		Lisce	Ossidate		Concave e convesse	Pochissime intersezioni	Media: 30÷100 m <sup>2</sup> /m <sup>3</sup> - 27÷1000 cm <sup>3</sup>
5	Argilla mamosa			Molto lisce	Ricoperte		Concoidale		Mediamente elevata: 100÷300 m <sup>2</sup> /m <sup>3</sup> - 1÷27 cm <sup>3</sup>
6				Estremamente lisce e traslucide					Elevata: > 300 m <sup>2</sup> /m <sup>3</sup> - < 1 cm <sup>3</sup>

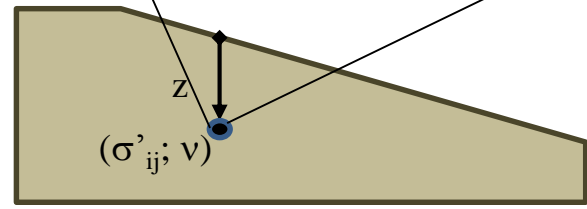
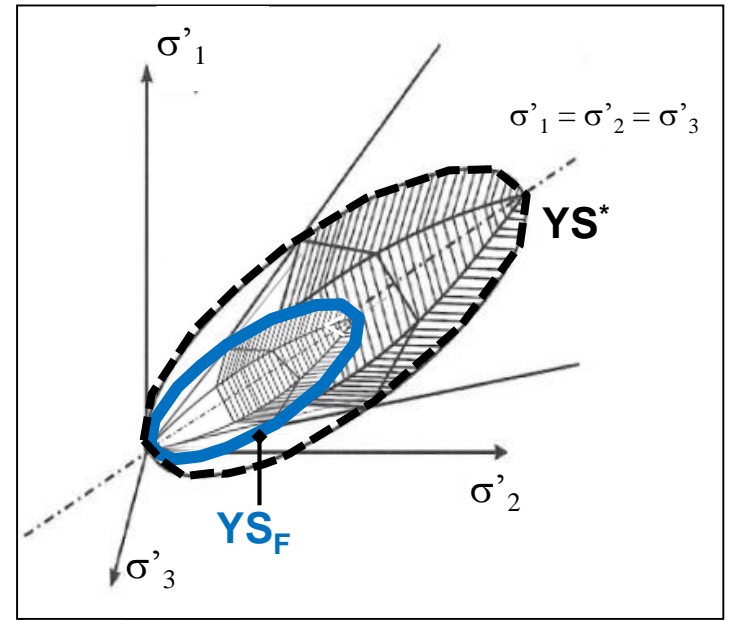
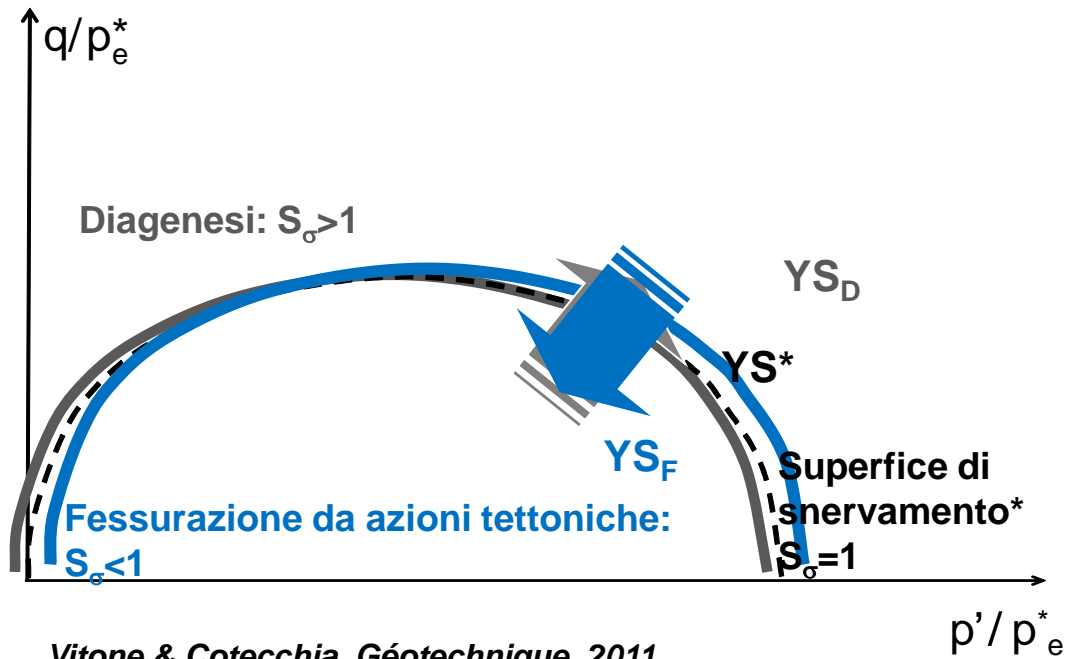
° Morgenstern & Eigenbrod, 1974; BS 8004, 1986

\* Fookes and Denness, 1969; ISRM, 1993

<sup>+</sup> Area delle discontinuità per unità di volume (m<sup>2</sup>/m<sup>3</sup>) e volume medio (m<sup>3</sup>, cm<sup>3</sup>) dell'elemento (Fookes & Denness, 1969, mod.)

<sup>-</sup> Coffey & Partners in Walker et al. (1987)

## Comportamento meccanico delle argille fessurate



Vitone & Cotecchia *Géotechnique*, 2011

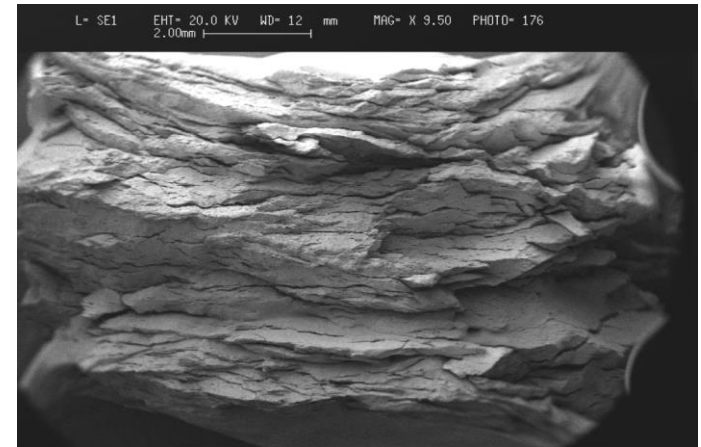
Vitone, Viggiani, Cotecchia, Hall - *Acta Geotechnica*, 2013

Cotecchia, Vitone, Santaloia, Pedone, Bottiglieri - *Landslides*, 2014

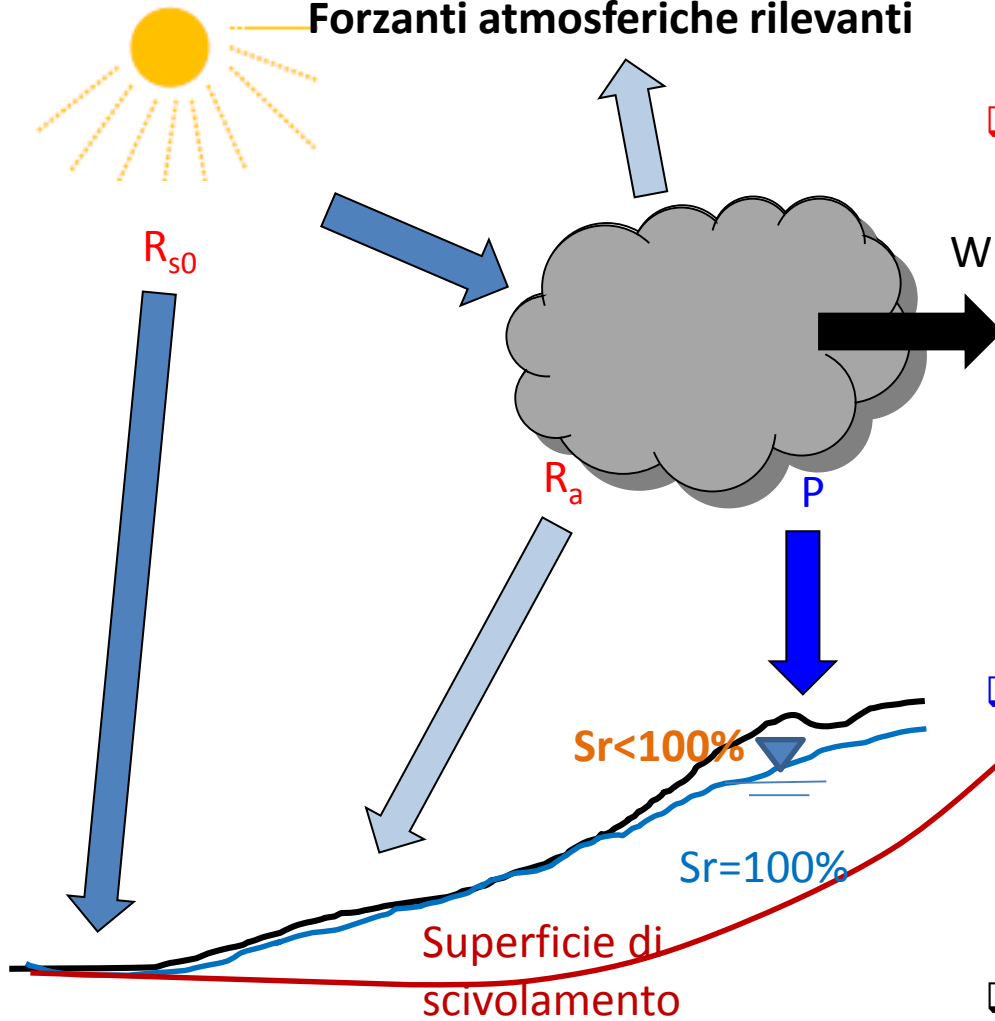
**Pendii sede di argille fessurate o di bande di taglio pre-esistenti  
sono spesso sede di attività franosa connessa al clima**



**Volturino (Lollino et al. 2010)**



## Forzanti atmosferiche rilevanti



### Processi termici

- ✓ Radiazione solare diretta (onda corta)
- ✓ Variazione della temperatura atmosferica per assorbimento di radiazione
- ✓ Radiazione atmosferica (onda lunga)

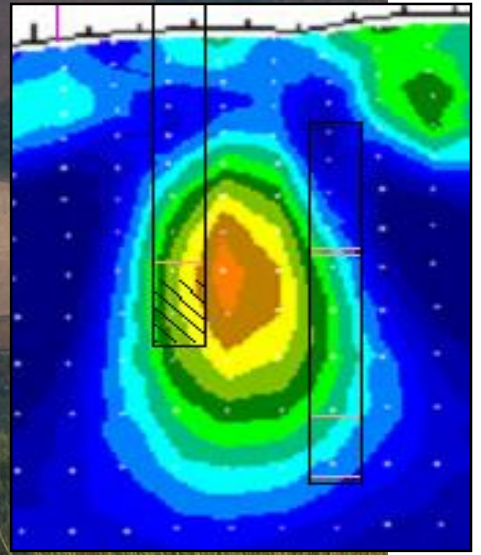
### Processi idrici

- ✓ Formazione nuvole
- ✓ Precipitazioni

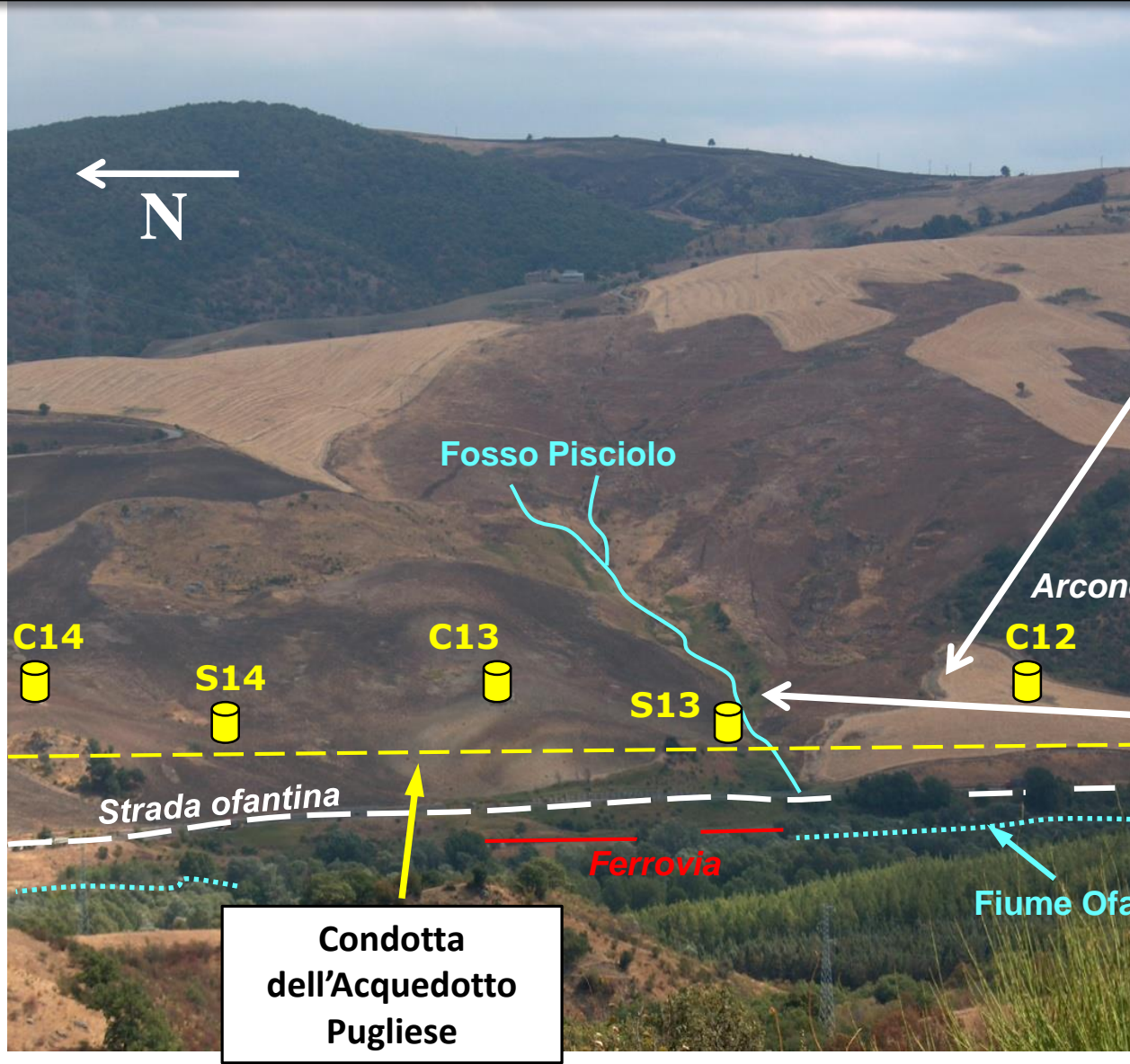
### Movimento di masse d'aria



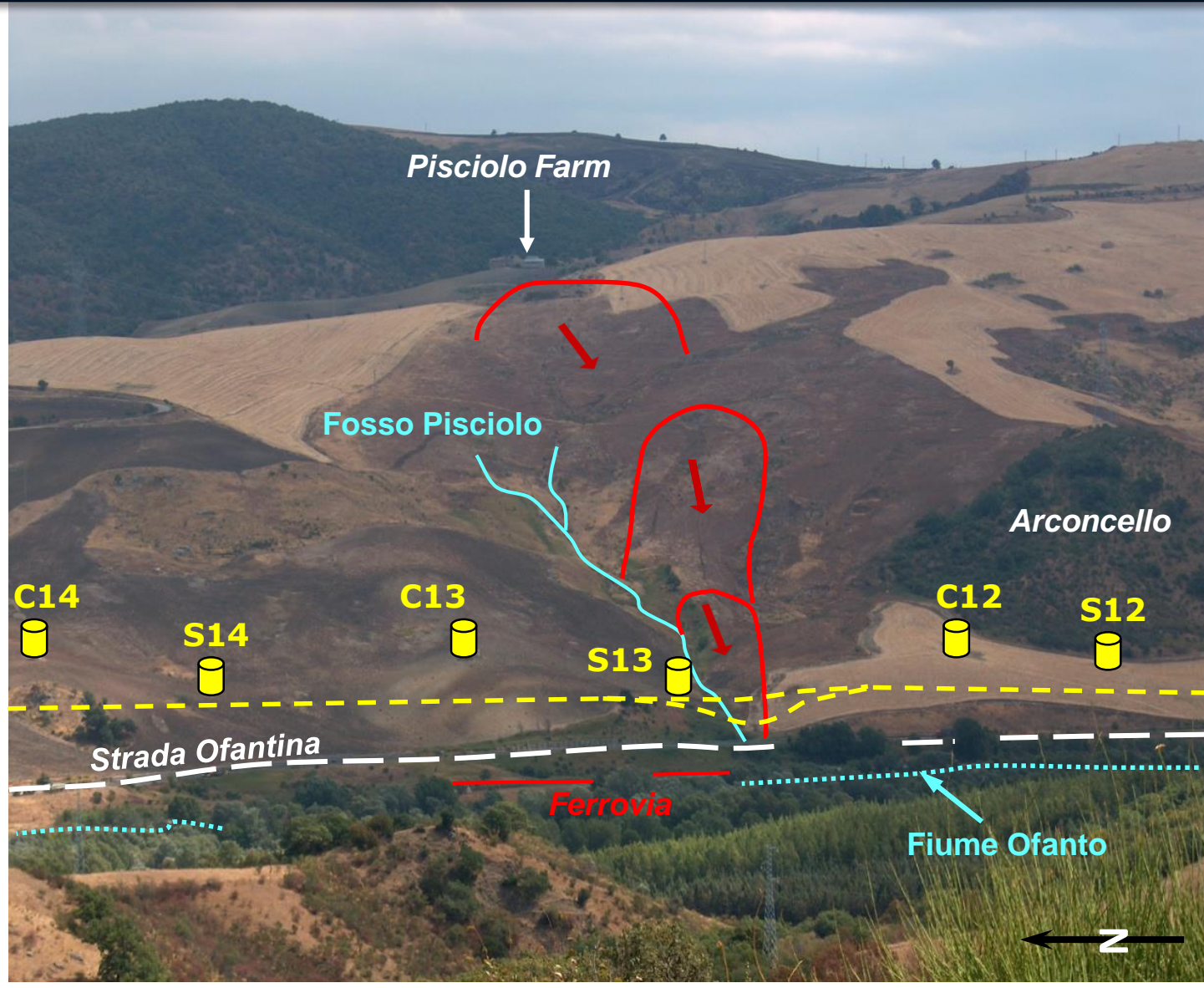
# FRANA DI PISICOLO (MELFI)











(Cotecchia et al., 2011, 2014, 2015)





Fosso Pisciole

Arconcello



C12

S12

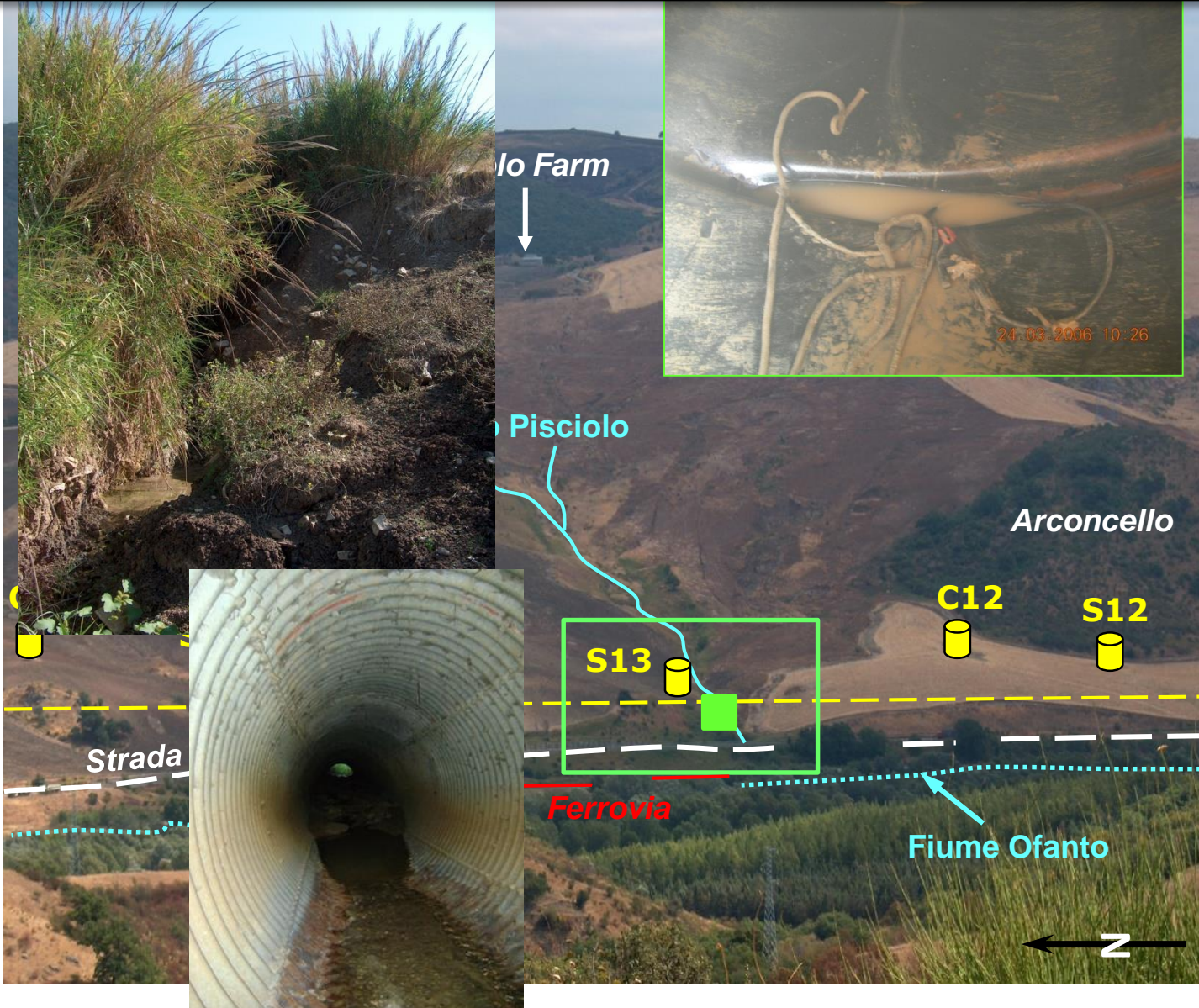
Danni all'infrastruttura dal 2003

Ferrovia

Fiume Ofanto







**Danni all'infrastruttura dal 2003**

(Cotecchia et al., 2011, 2014, 2015)



## Campagna geognostica (2009-2010)

Sondaggi a carotaggio continuo

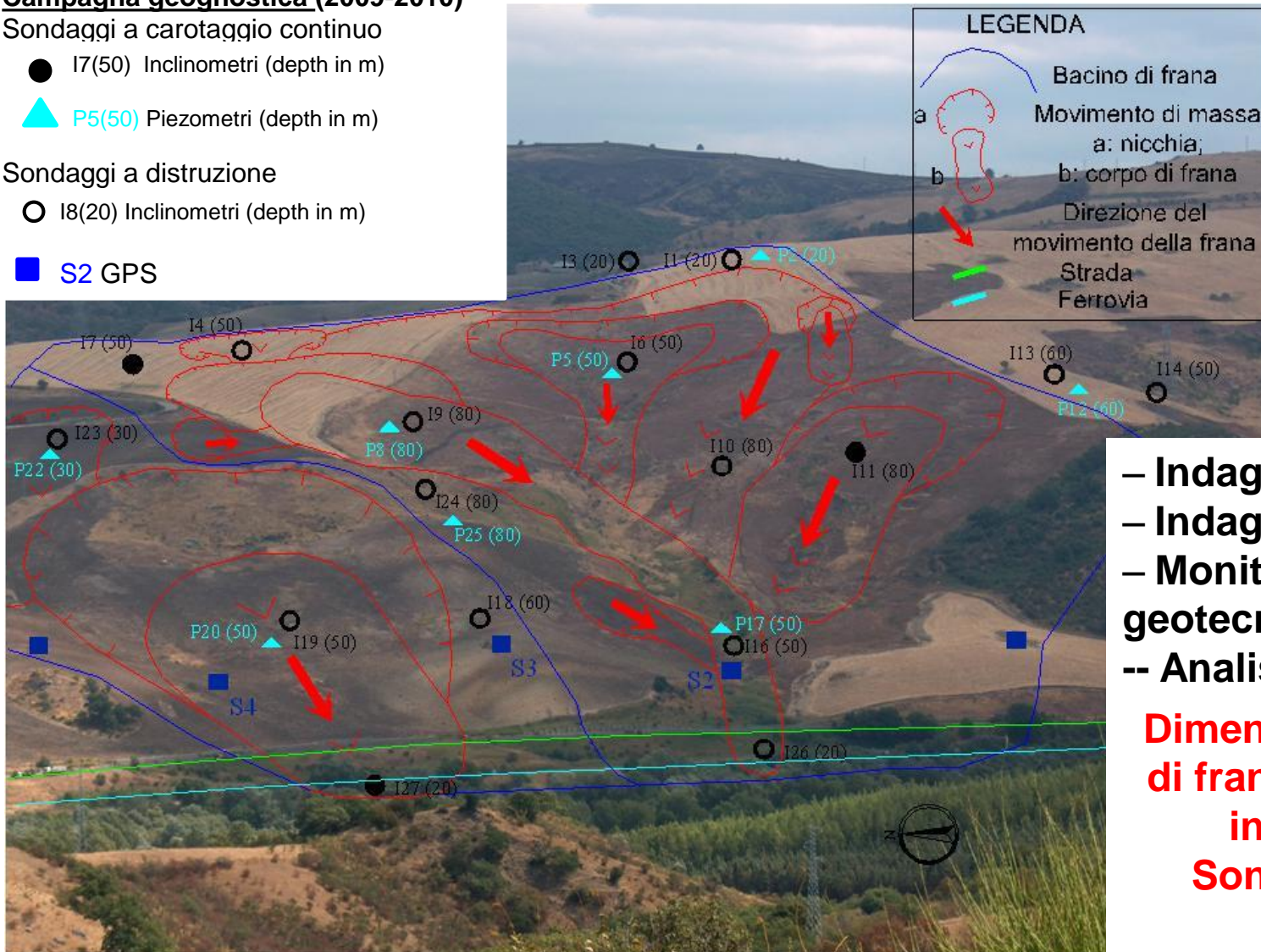
● I7(50) Inclinatori (depth in m)

▲ P5(50) Piezometri (depth in m)

Sondaggi a distruzione

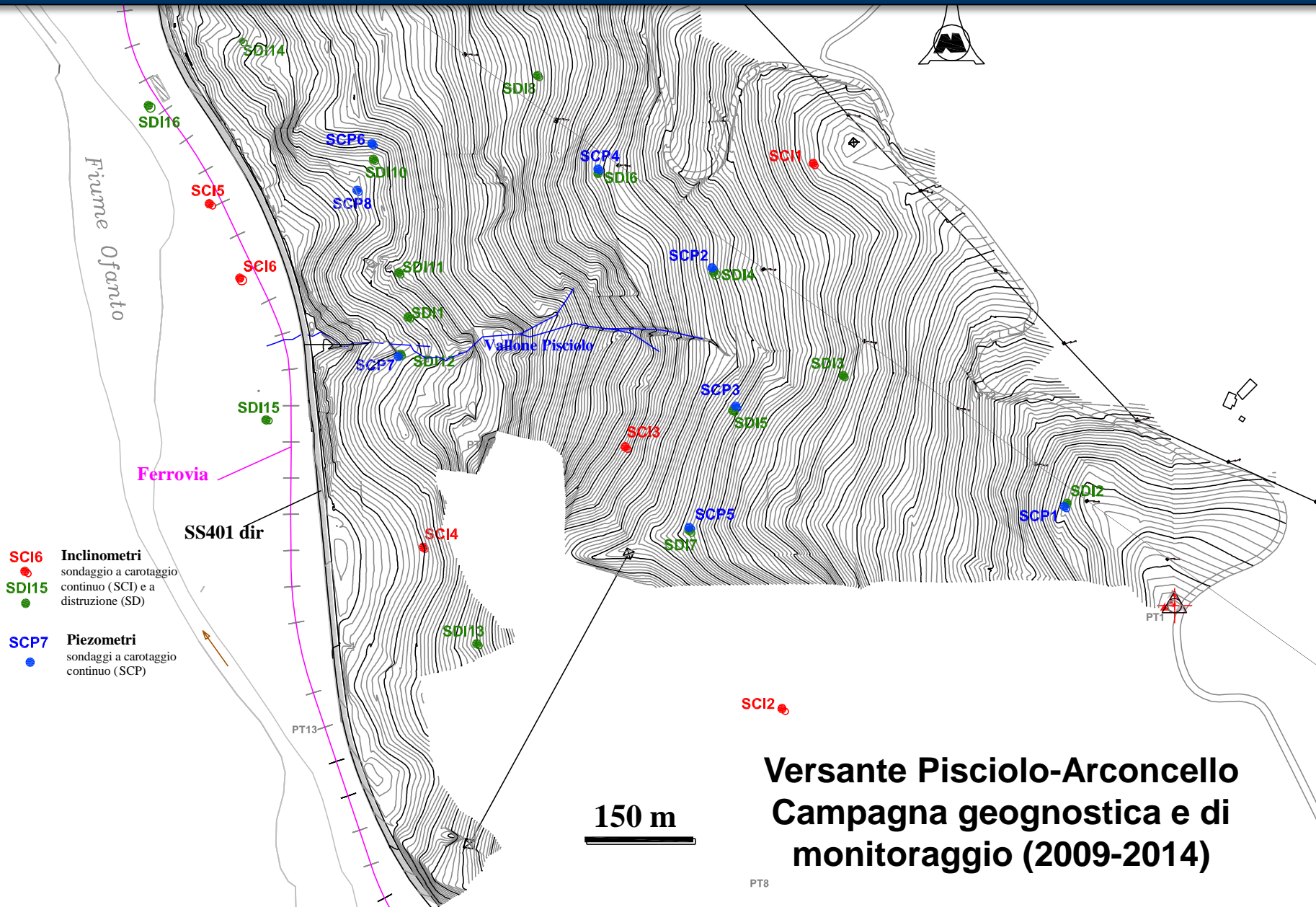
○ I8(20) Inclinatori (depth in m)

■ S2 GPS



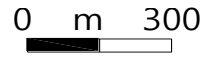
- Indagini in situ
- Indagini in laboratorio
- Monitoraggio geotecnico
- Analisi LEM



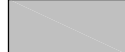





**Dimensioni dei corpi di frana ed eventuali interazioni?  
Sono profondi?  
Cause?**








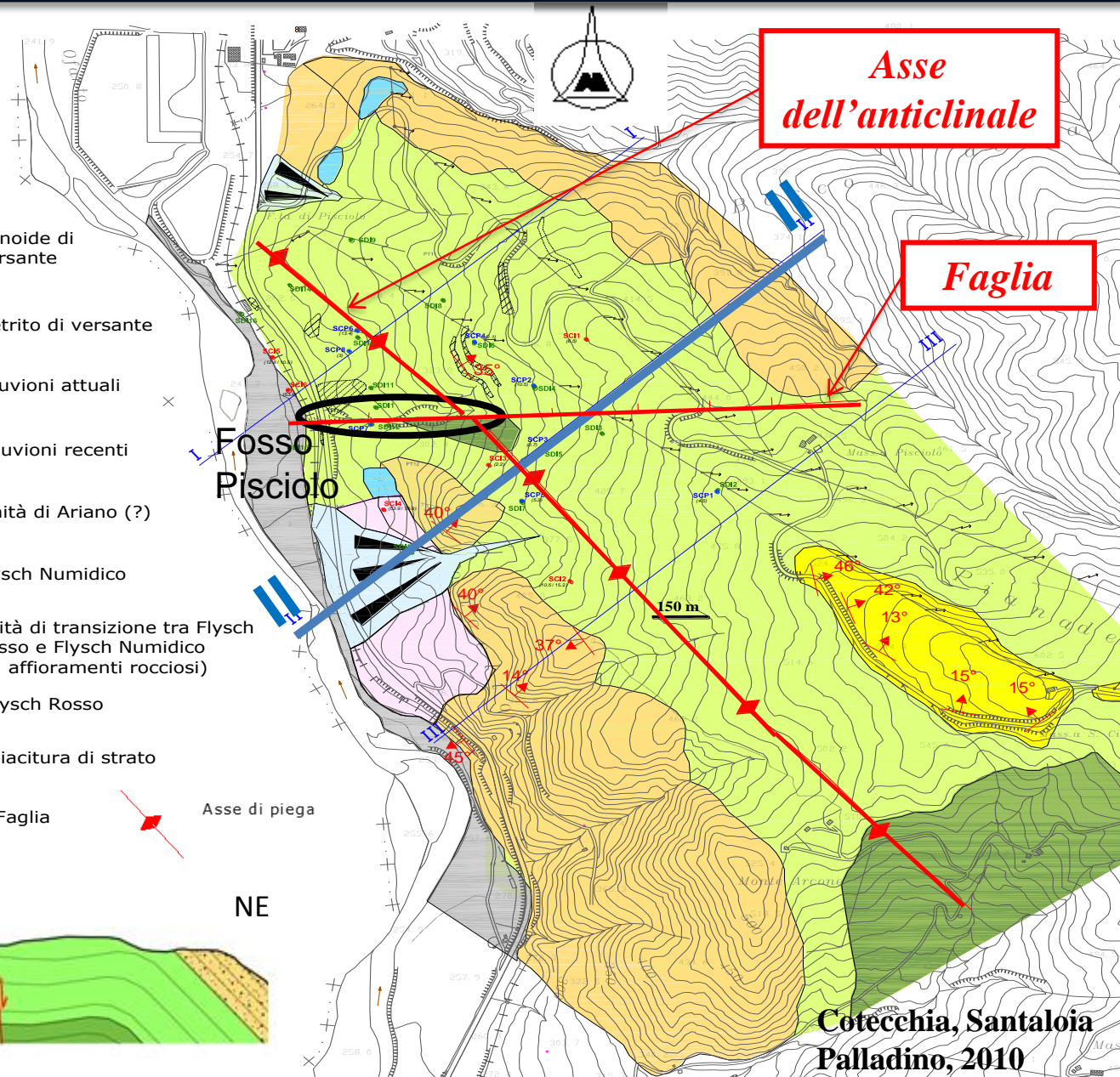
# Inquadramento geologico



-  Conoide di versante
-  Detrito di versante
-  Alluvioni attuali
-  Alluvioni recenti
-  Unità di Ariano (?)
-  Flysch Numidico
- a)  Unità di transizione tra Flysch Rosso e Flysch Numidico (a: affioramenti rocciosi)
-  Flysch Rosso

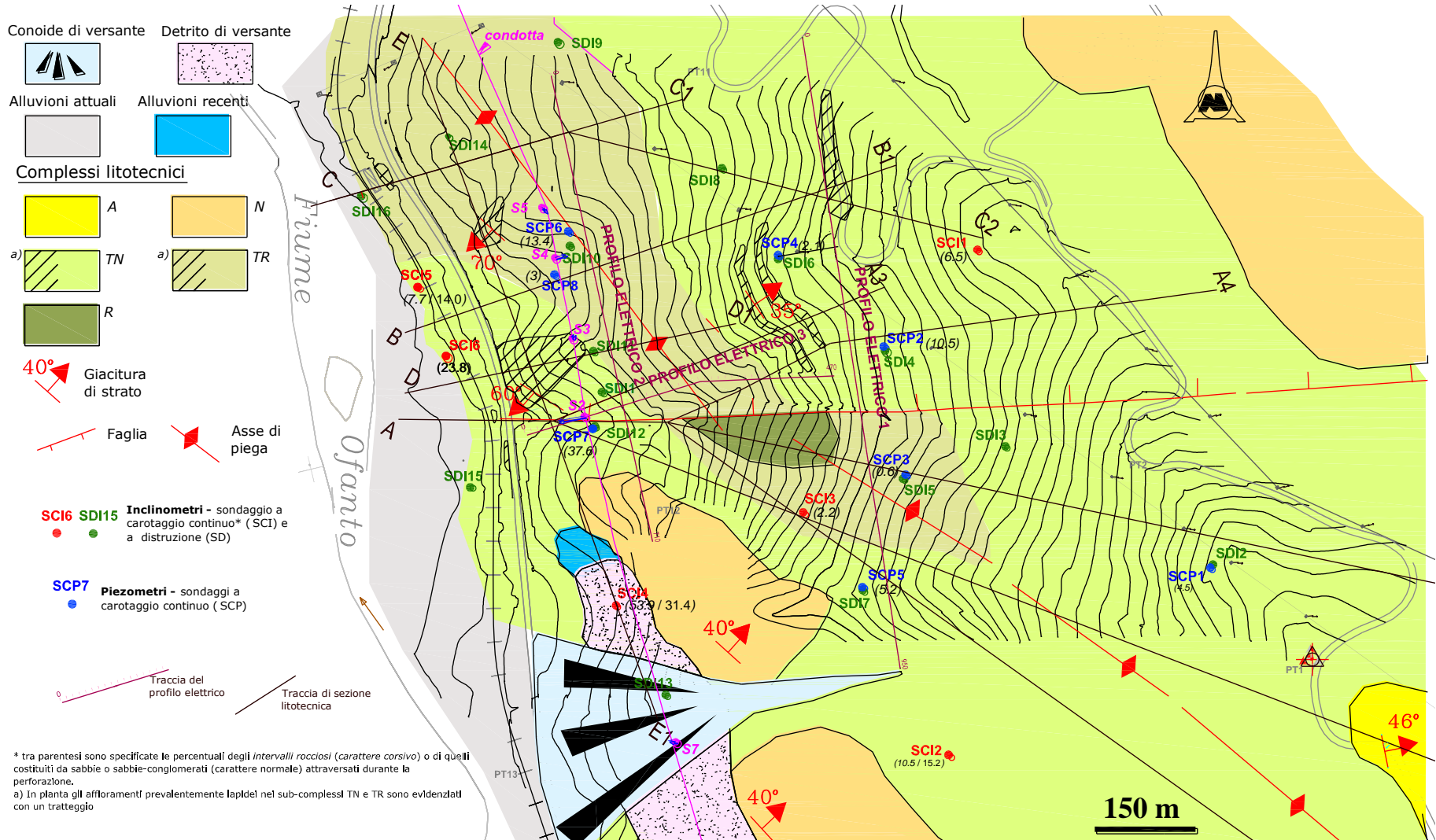
-  Giacitura di strato 42°
-  Faglia
-  Asse di piega

Sezione II

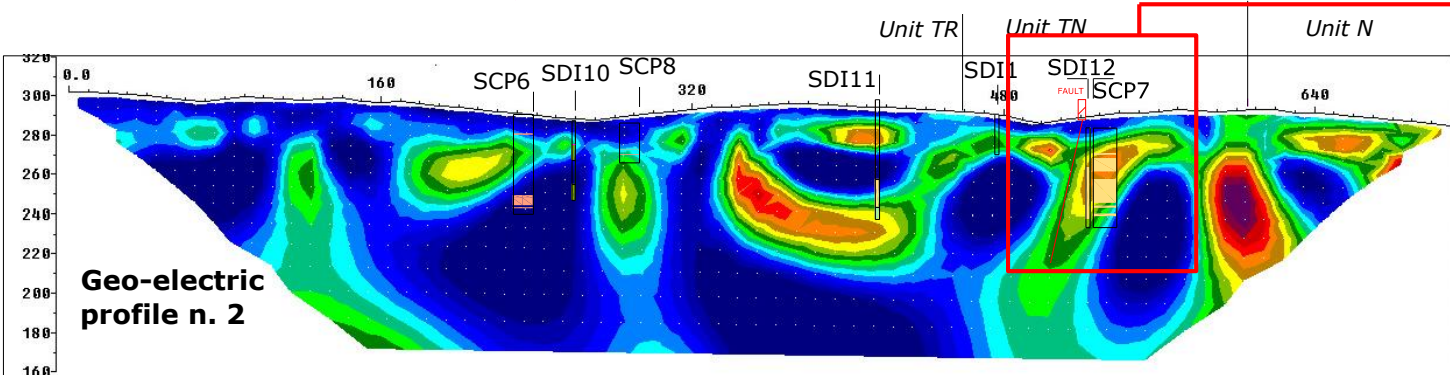
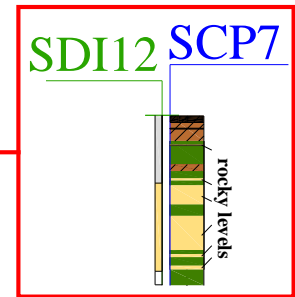
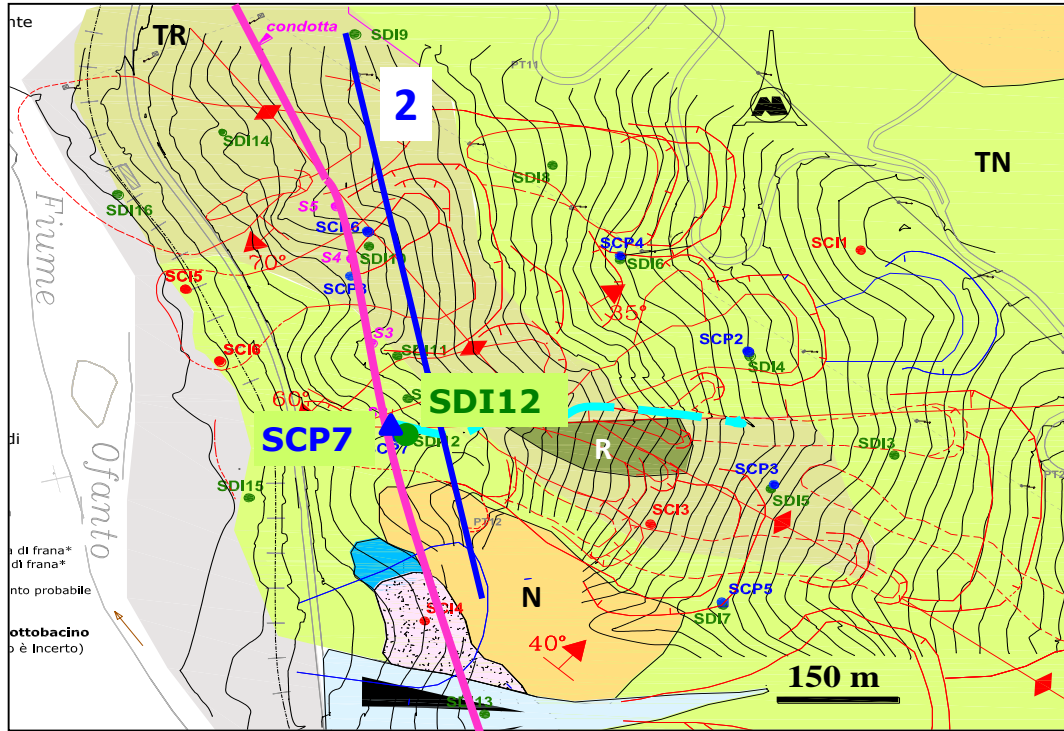




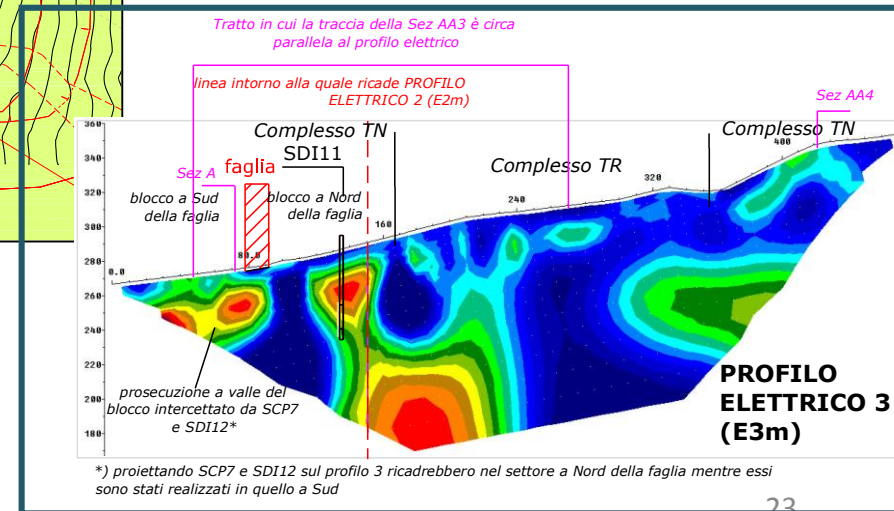
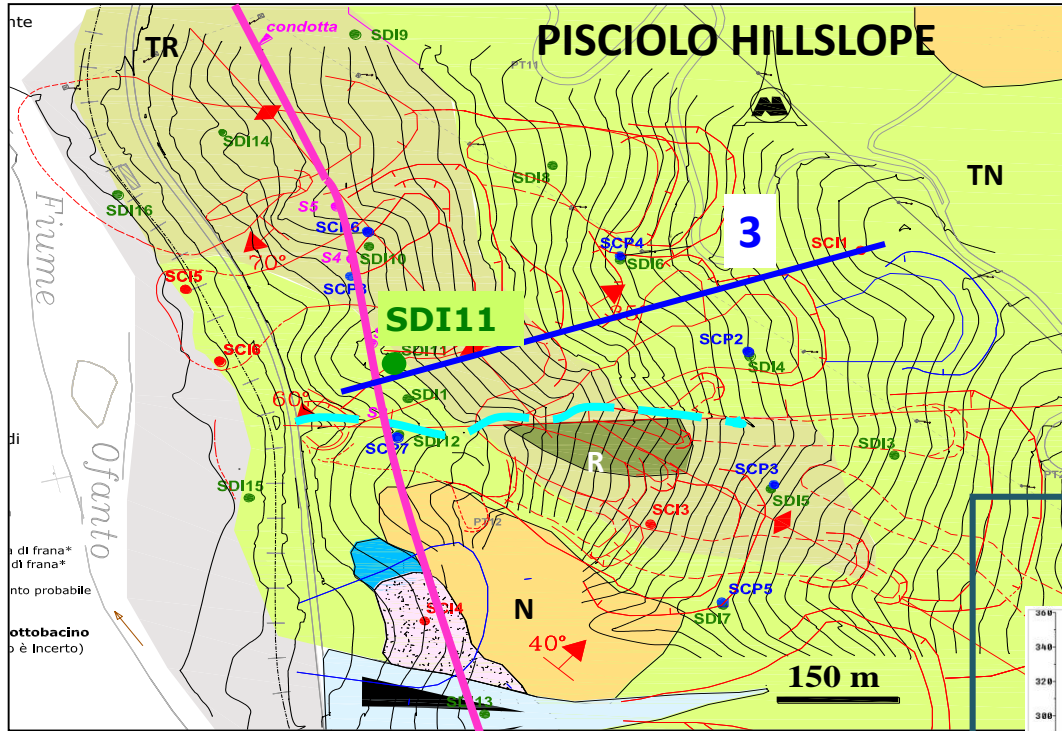
# Carta litotecnica del versante



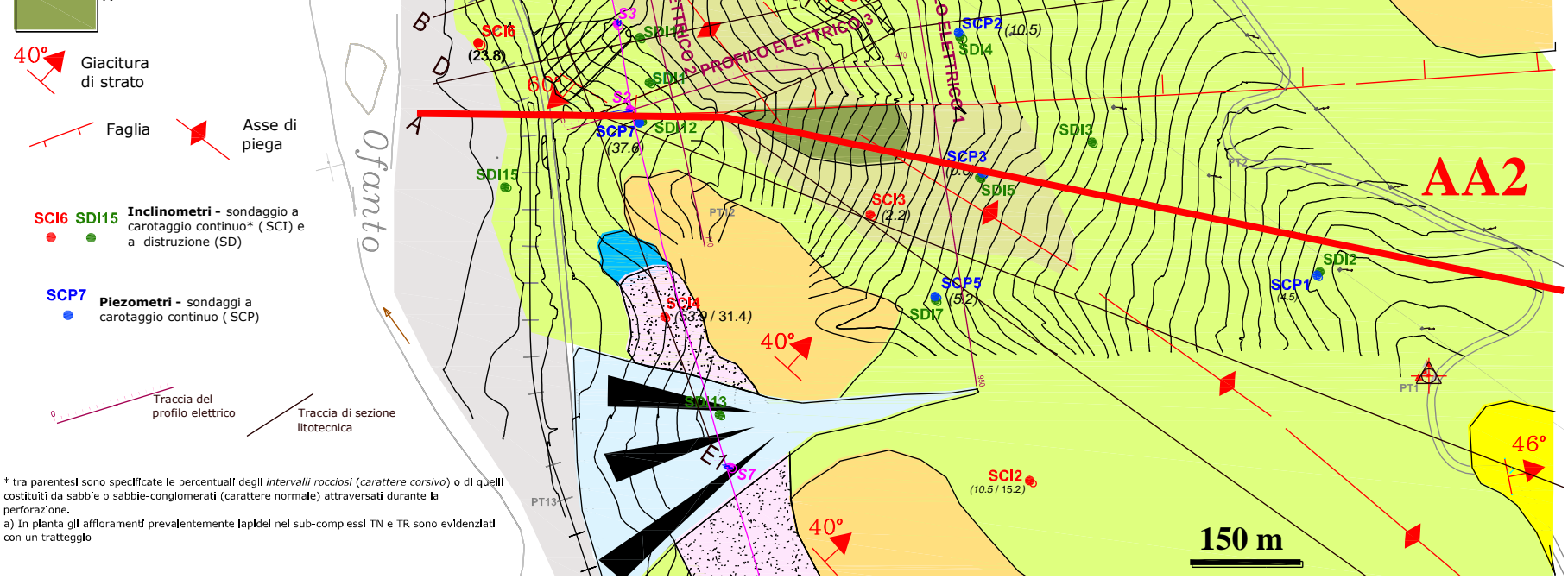
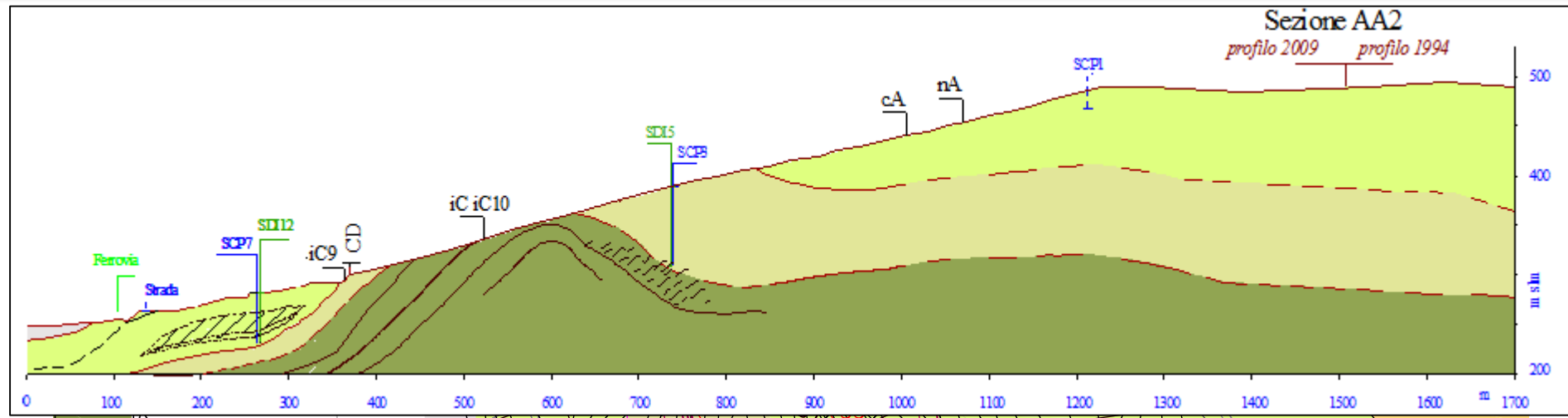
# Analisi stratigrafiche e profili geo-elettrici



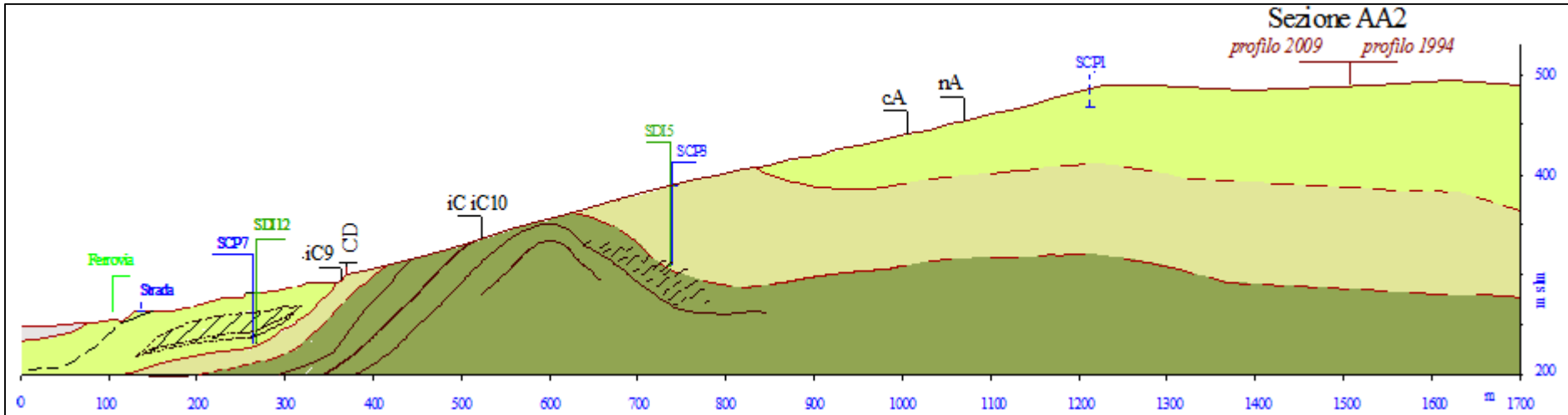
# Analisi stratigrafiche e profili geo-elettrici



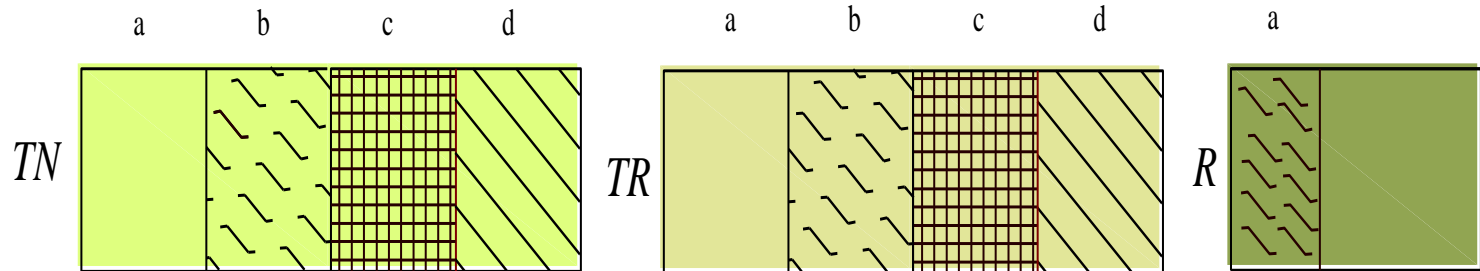




\* tra parentesi sono specificate le percentuali degli *intervalli rocciosi* (carattere corsivo) o di quelli costituiti da sabbie o sabbie-conglomerati (carattere normale) attraversati durante la perforazione.  
a) In pianta gli affioramenti prevalentemente lapidei nel sub-complexi TN e TR sono evidenziati con un tratteggio

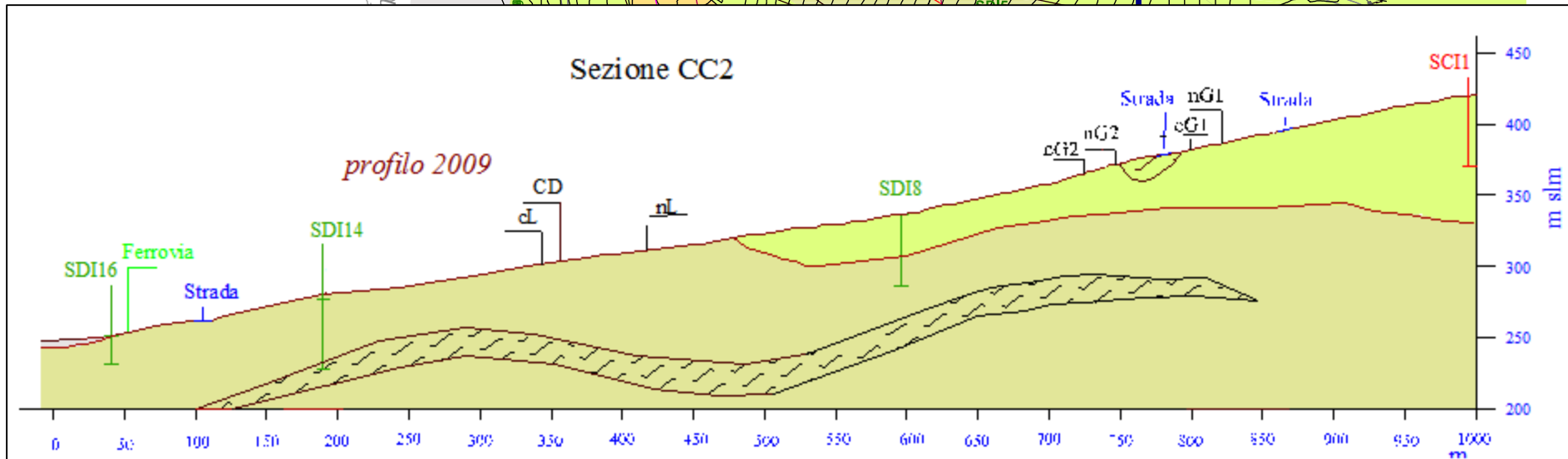
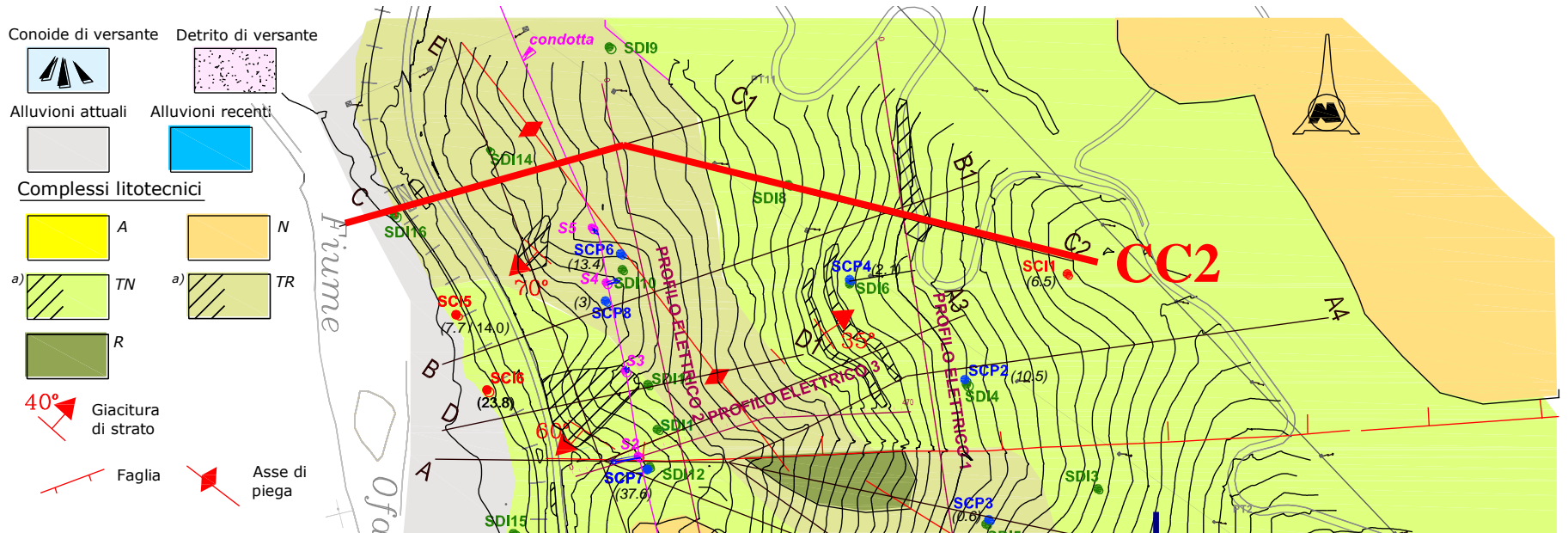


## Sezione AA2





# Carta litotecnica del versante

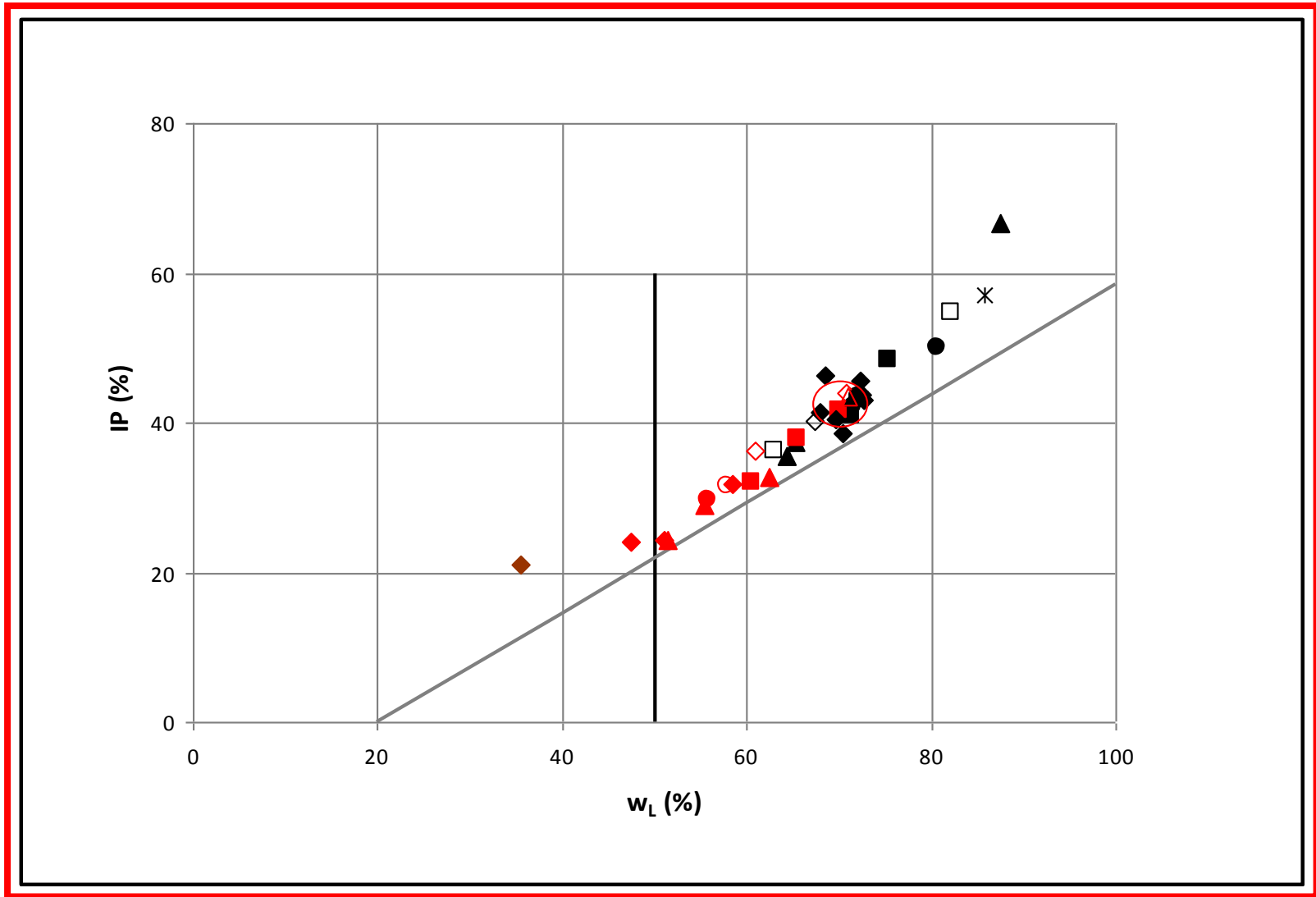


	TERRENO INTEGRO		NATURA DELLE DISCONTINUITÀ			ORIENTAZIONE DELLE DISCONTINUITÀ	GEOMETRIA DELLE DISCONTINUITÀ		
	Principale natura del sedimento <b>A</b>	Resistenza non drenata <b>B</b>	Tipo <b>C</b>	Rugosità <b>D</b>	Stato <b>E</b>	<b>F</b>	Forma <b>G</b>	Continuità <b>H</b>	Intensità <b>I</b>
1	Argilla	Argillite	Deposizionale	Molto scabre	Inalterate	Singola	Piana	Continue	Molto bassa: $< 3 \text{ m}^2/\text{m}^3 - > 1 \text{ m}^3$
2	Limo	Argilla consistente	Rilassate						Bassa: $3 \div 10 \text{ m}^2/\text{m}^3 - 0.027 \div 1 \text{ m}^3$
3	Argilla limosa	Argilla mediamente consistente	Indotazioni						Medio-bassa: $10 \div 30 \text{ m}^2/\text{m}^3 - 0.001 \div 0.027 \text{ m}^3$
4	Limo argilloso	Argilla soffice							Media: $30 \div 100 \text{ m}^2/\text{m}^3 - 27 \div 1000 \text{ cm}^3$
5	Argilla marnosa								Mediamente elevata: $100 \div 300 \text{ m}^2/\text{m}^3 - 1 \div 27 \text{ cm}^3$
6				Estremamente lisce e traslucide					Elevata: $> 300 \text{ m}^2/\text{m}^3 - < 1 \text{ cm}^3$

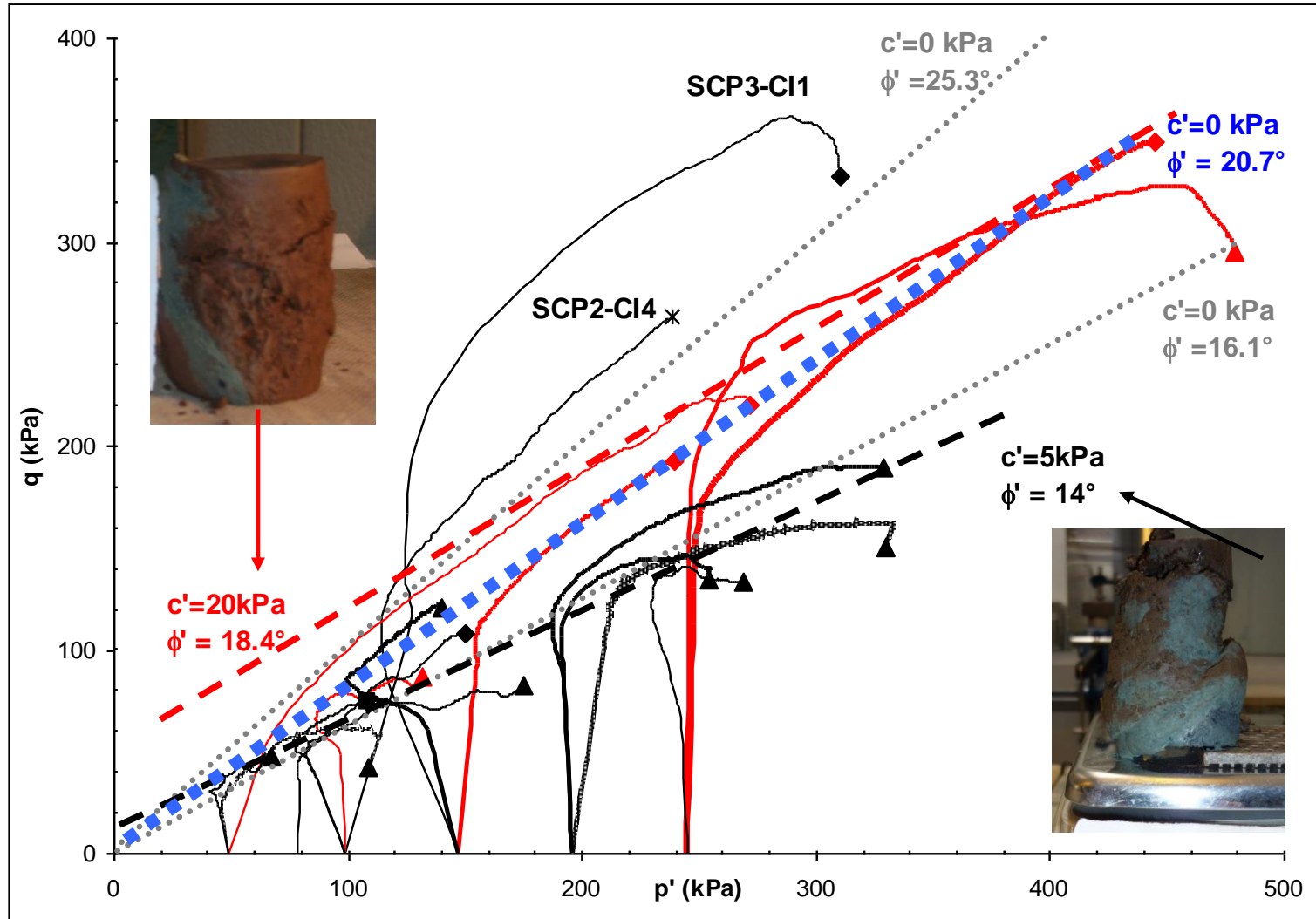




# Carta di Plasticità di Casagrande

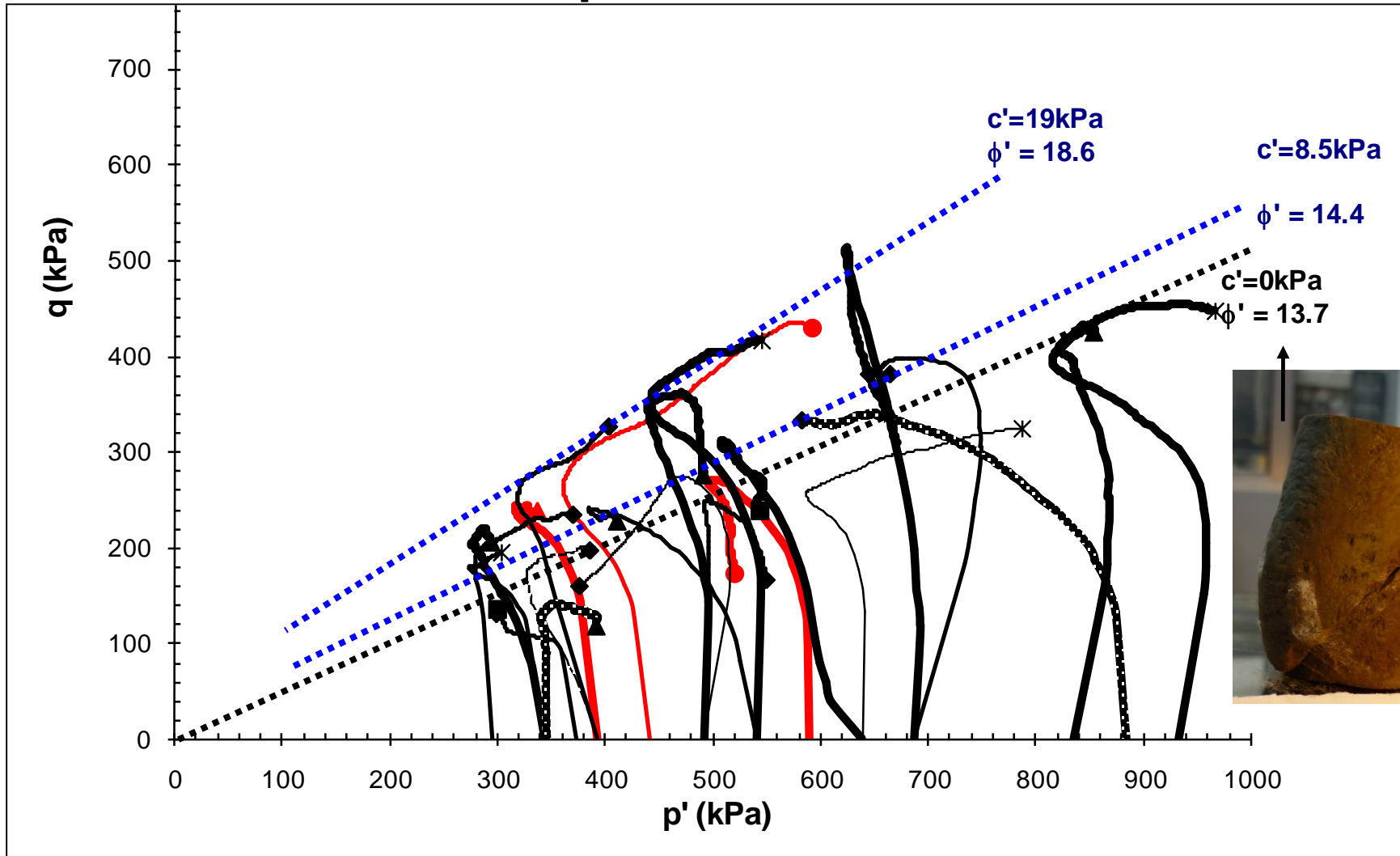


# Parametri di resistenza desunti da prove TRX-CIU

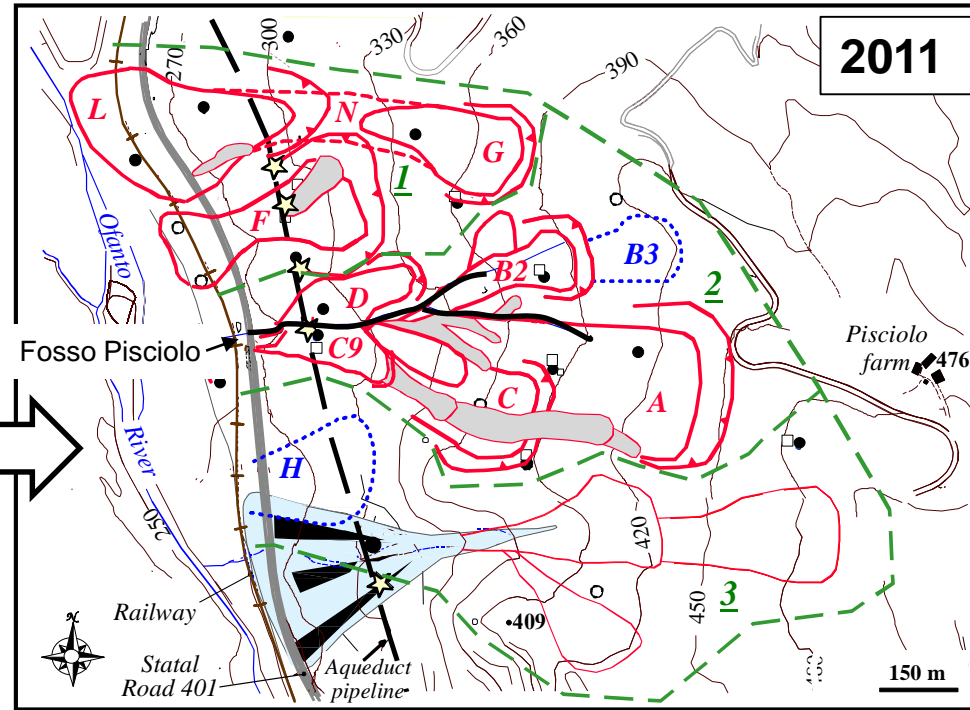
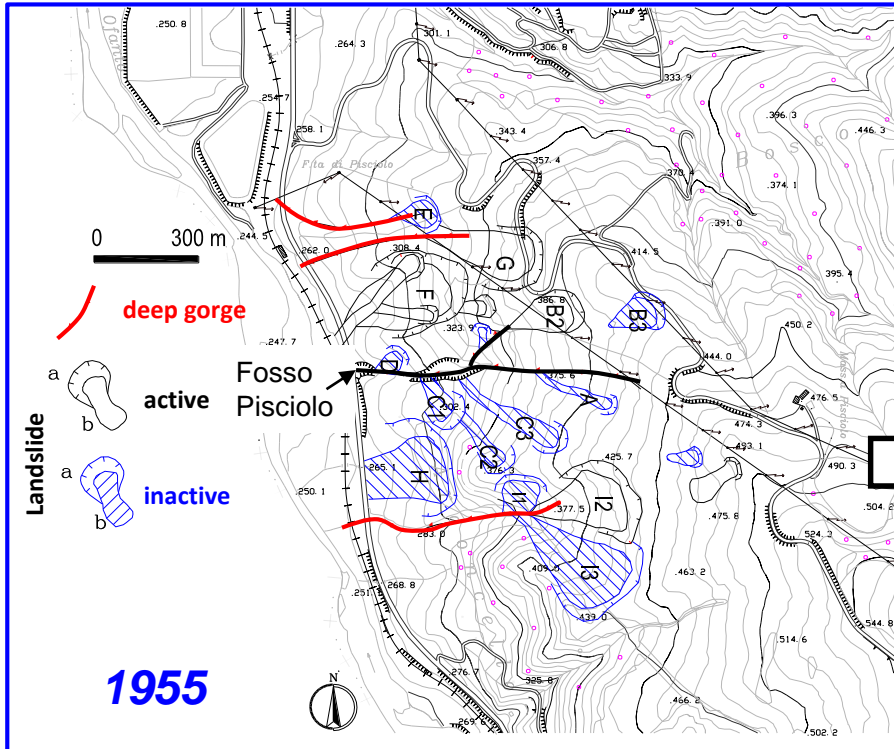




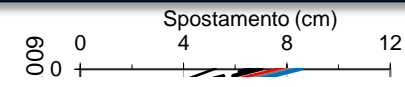
## Parametri di resistenza desunti da prove TRX-CIU



## 50 anni: evoluzione della fenomeno franoso

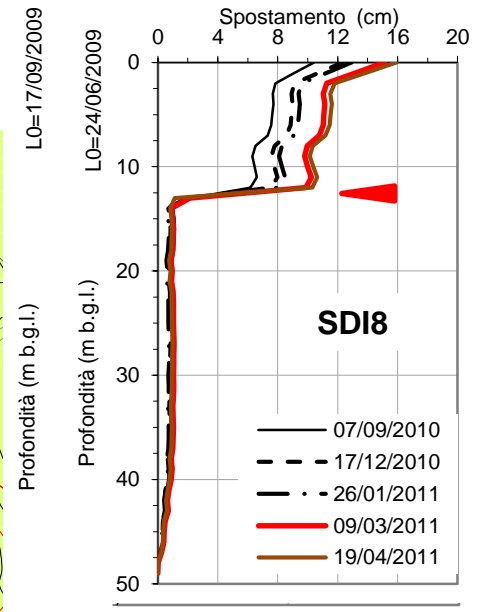
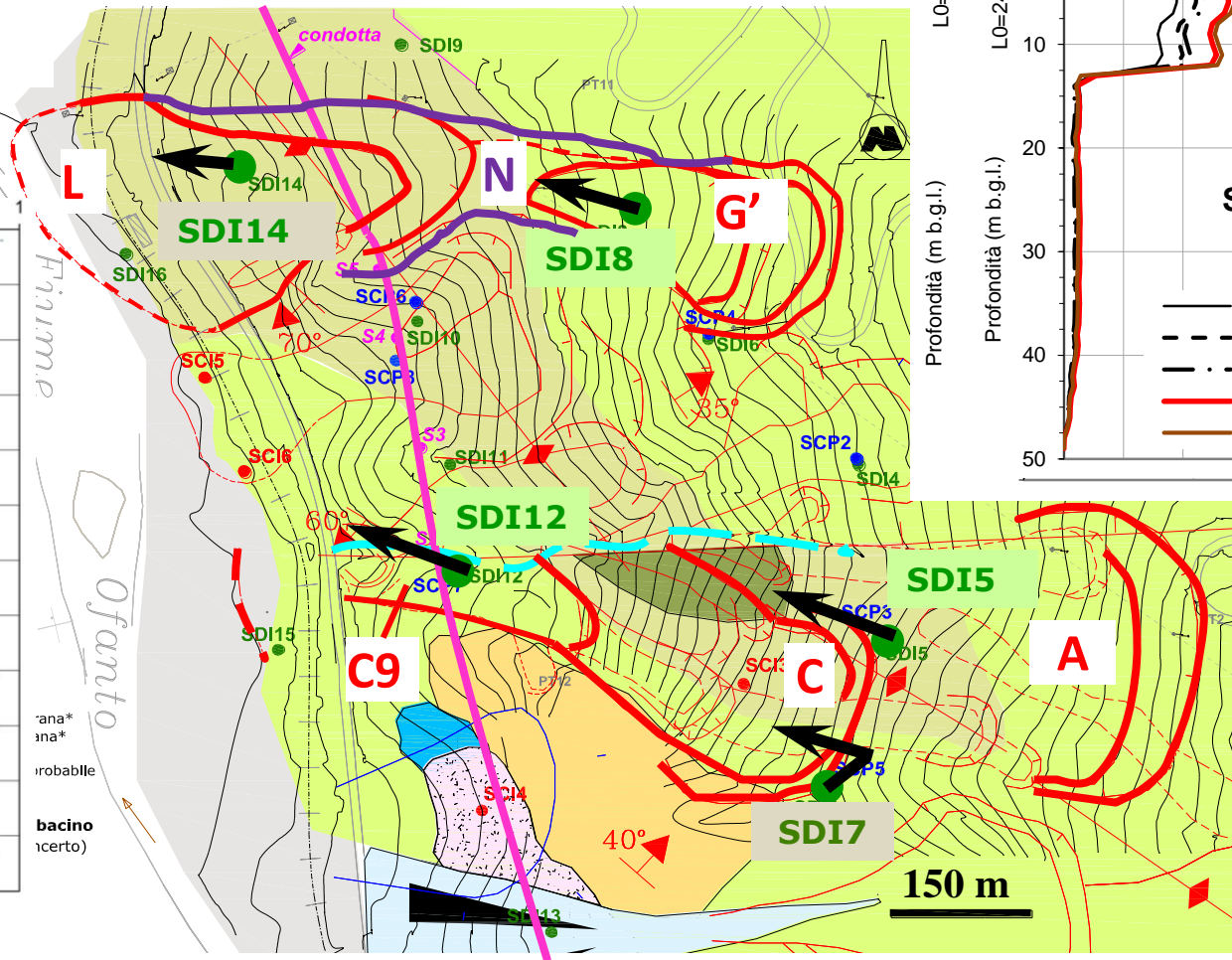
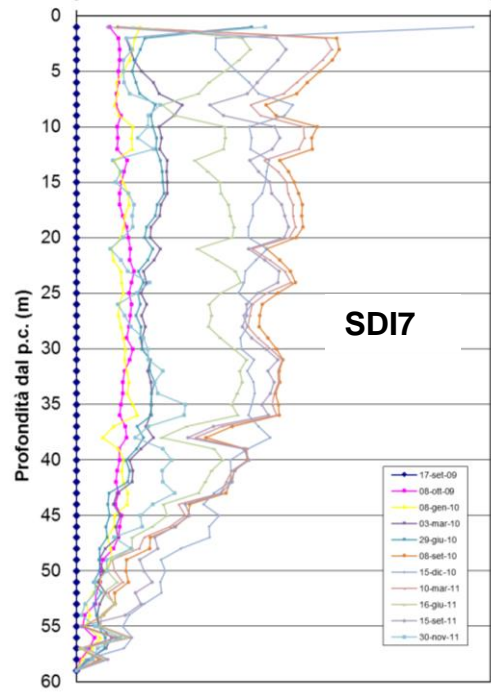
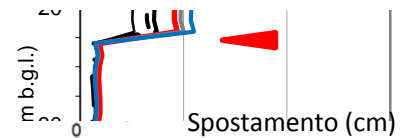


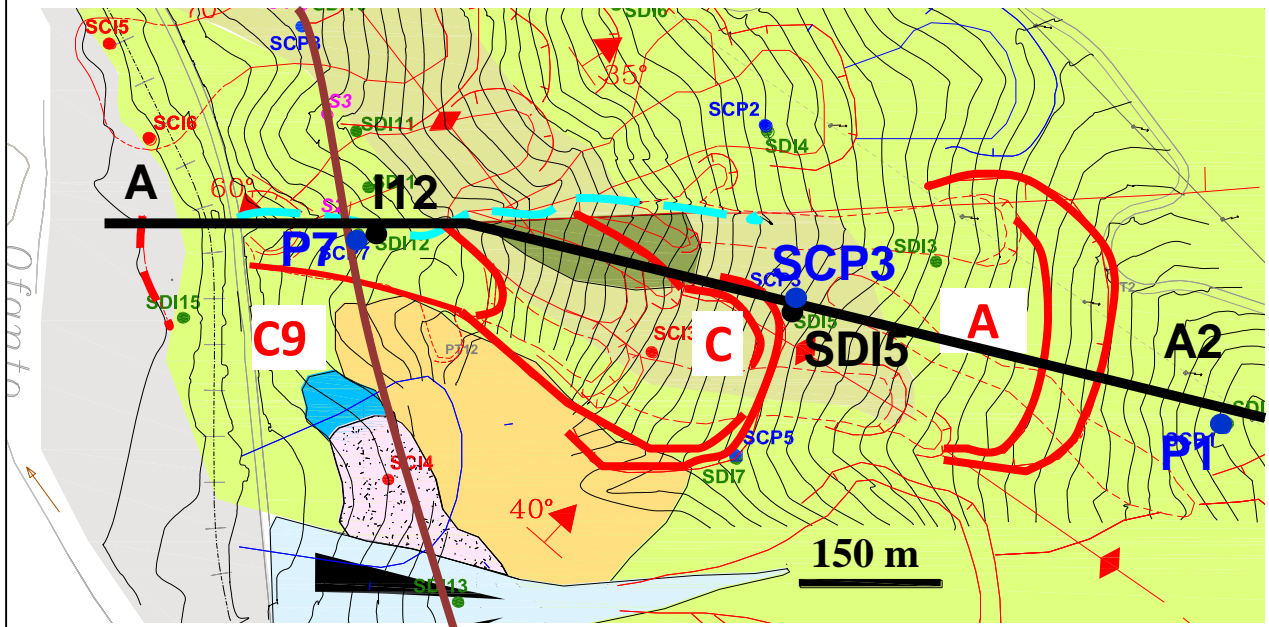
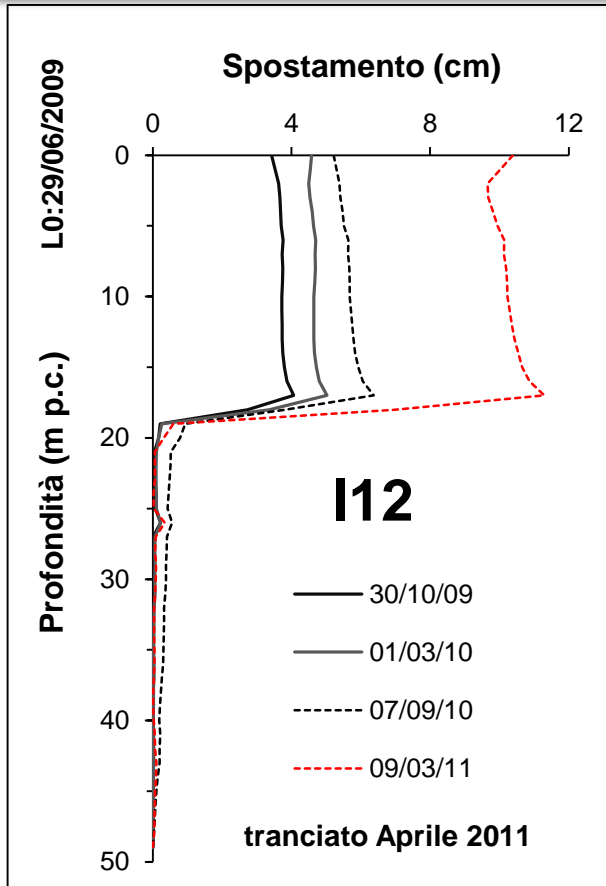




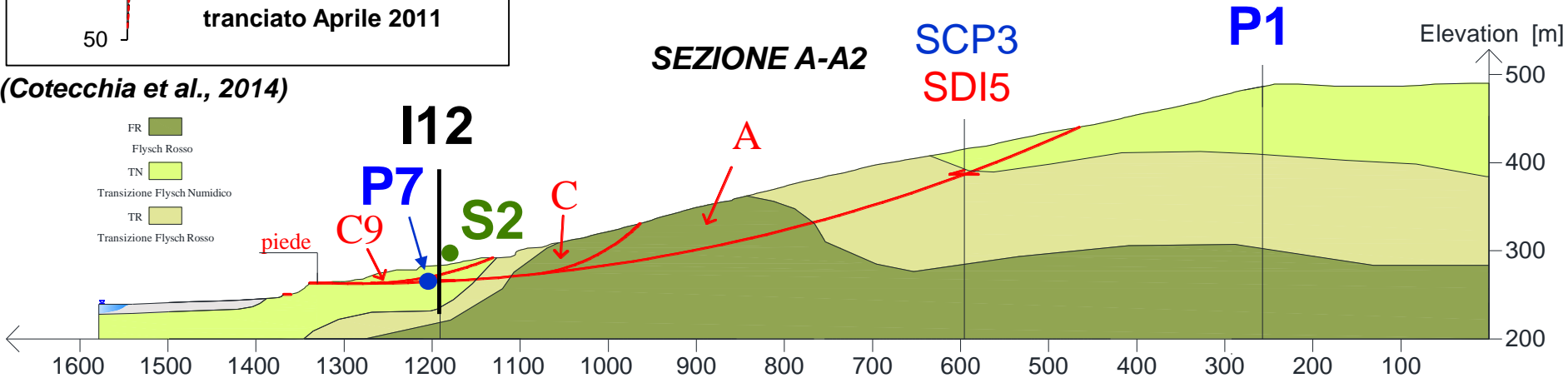
**Corpi L, G, C, C9**  
1.2 cm/anno <math>v < 18 \text{ cm/anno}</math>

**Corpo A**  
 $V_{\text{media}} = 0.7 \text{ cm/anno}$



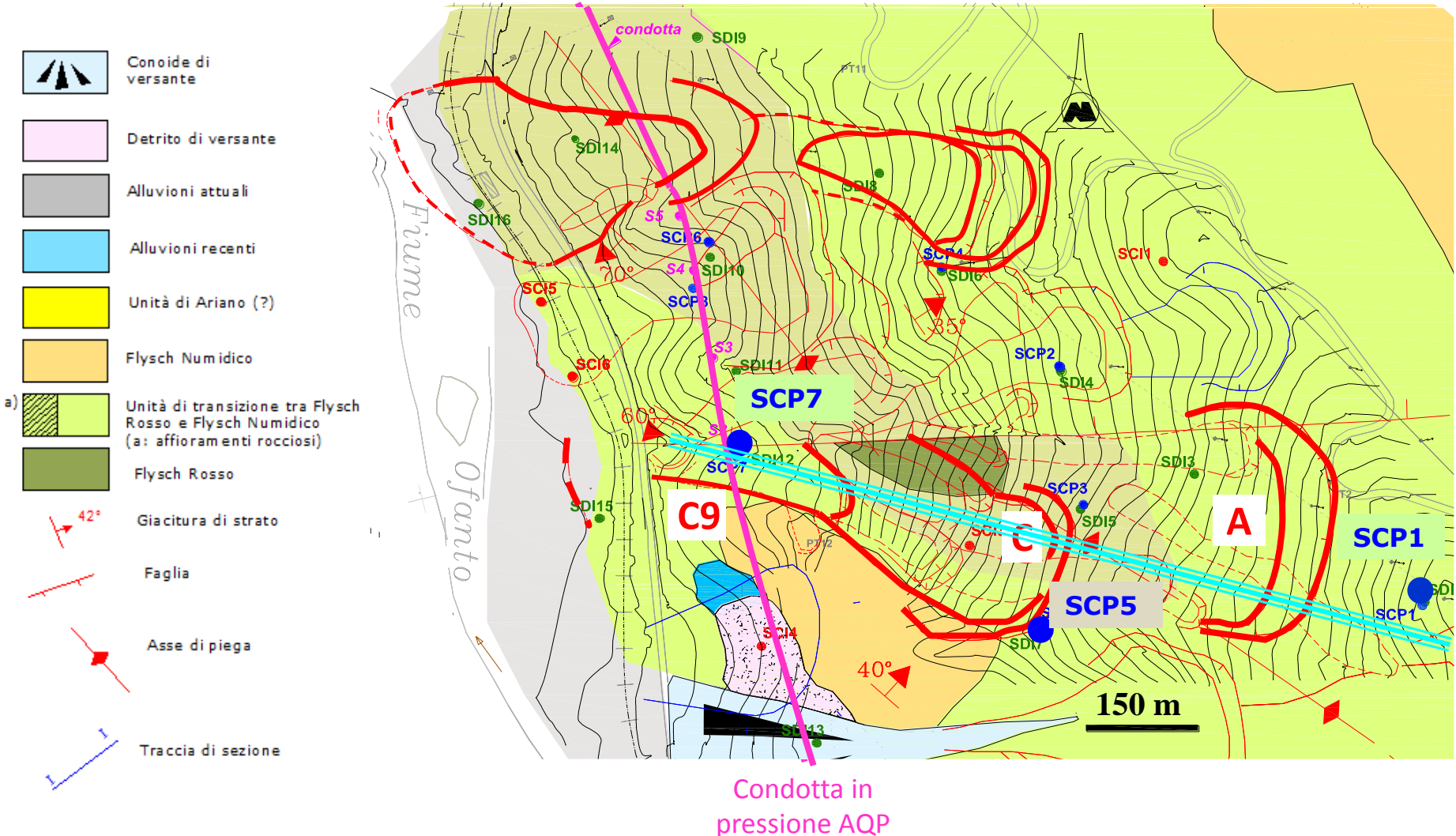


(Cotecchia et al., 2014)

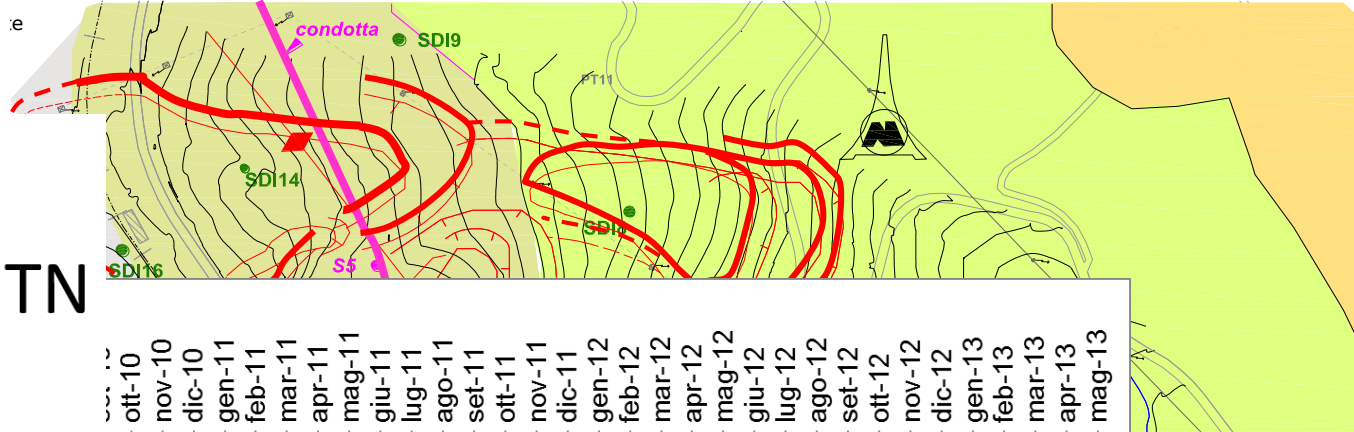
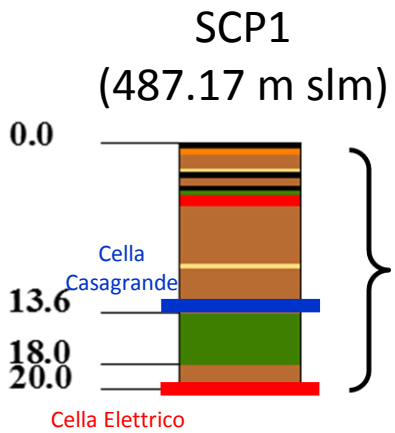




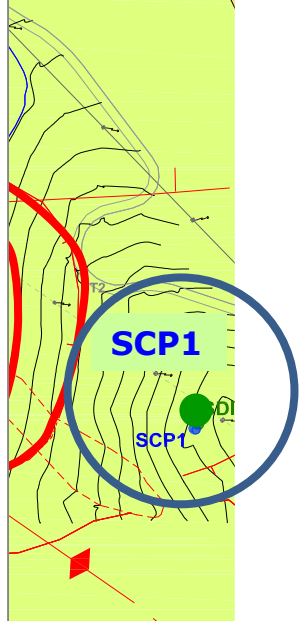
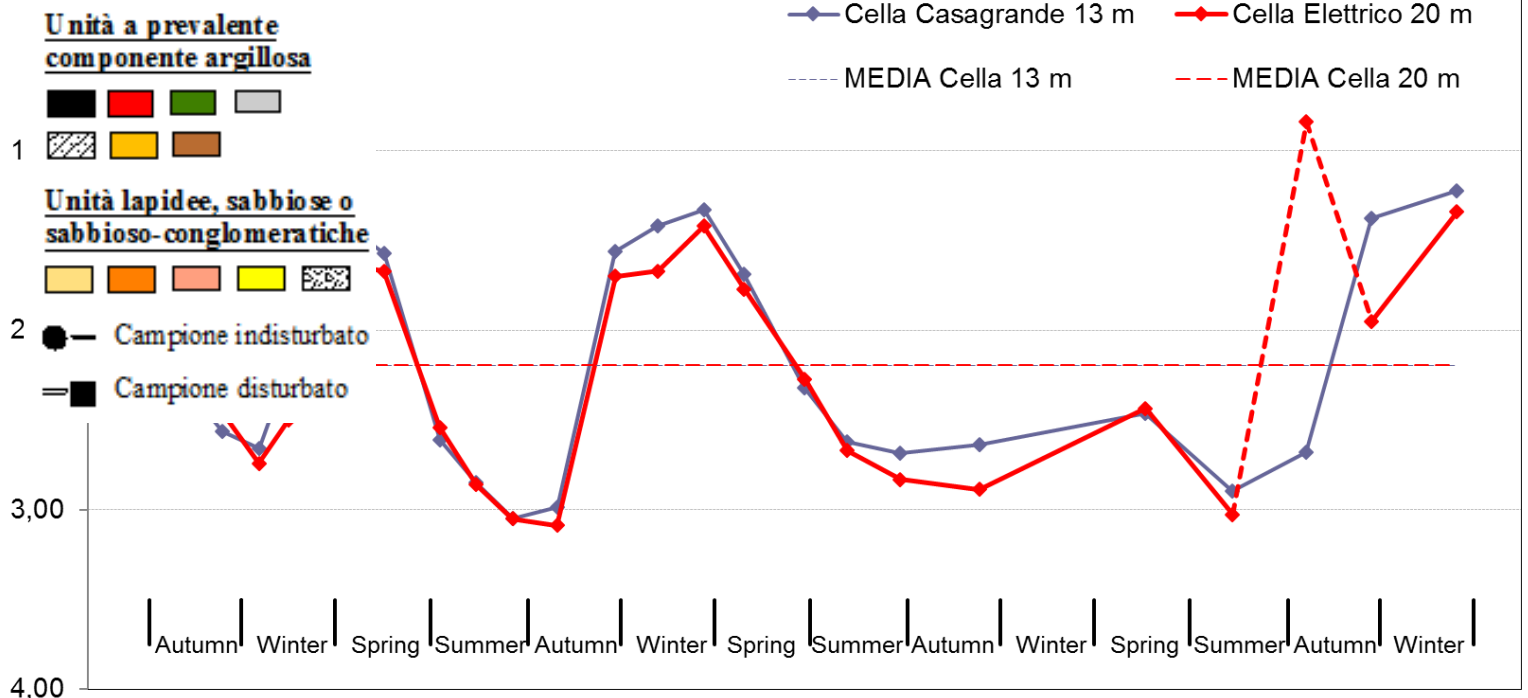
## Piezometrie – Piezometri Casagrande ed Elettrici



## Piezometrie – Piezometri Casagrande ed Elettrici



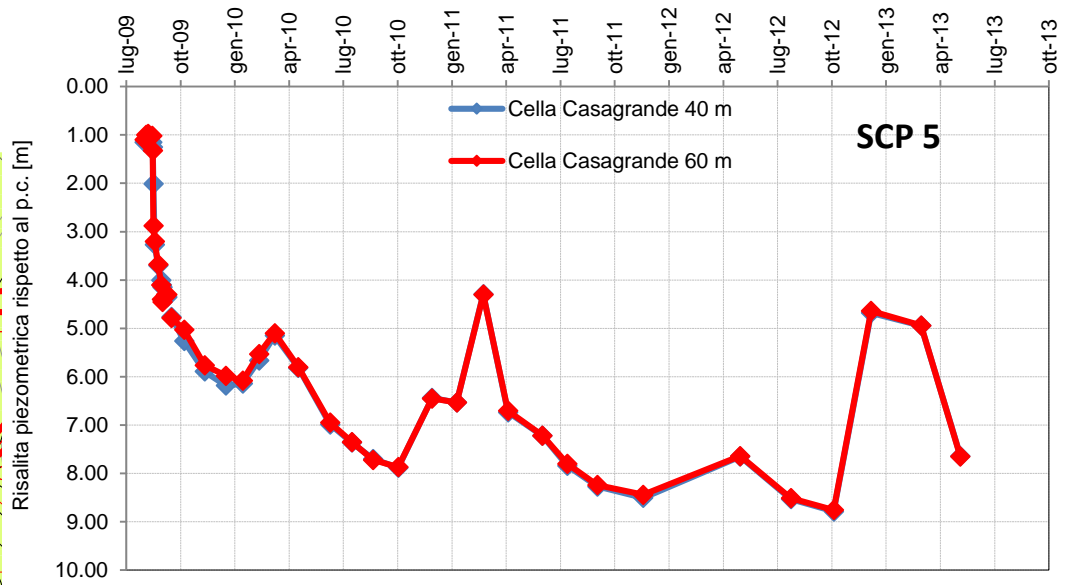
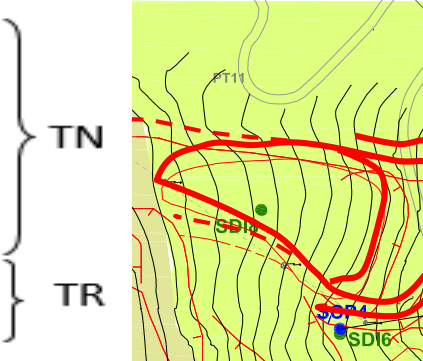
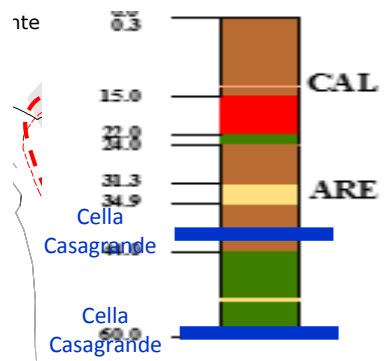
Risalta piezometrica rispetto al p.c. [m]





## Piezometrie – Piezometri Casagrande ed Elettrici

**SCP5**  
(387 m slm)



**Unità a prevalente componente argillosa**

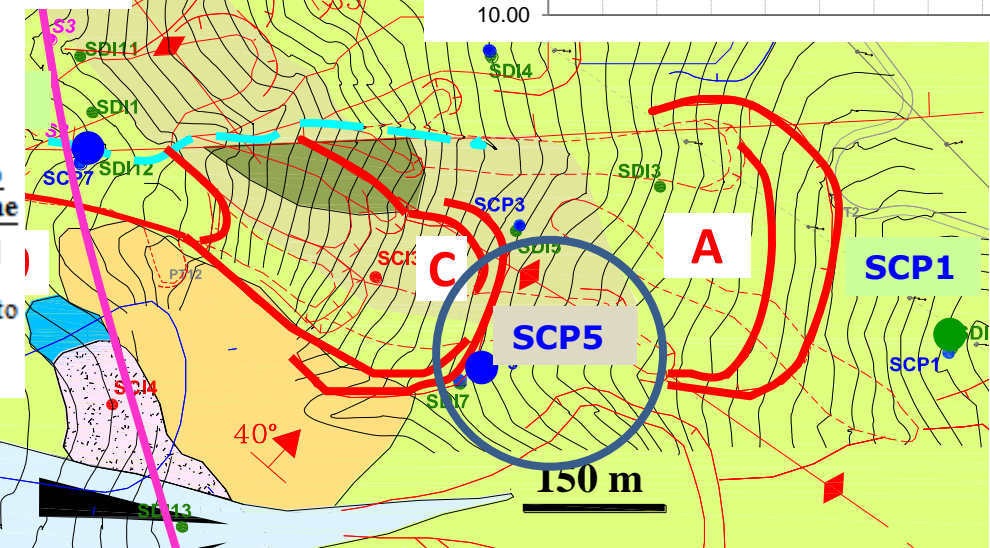


**Unità lapidee, sabbiose o sabbioso-conglomeratiche**

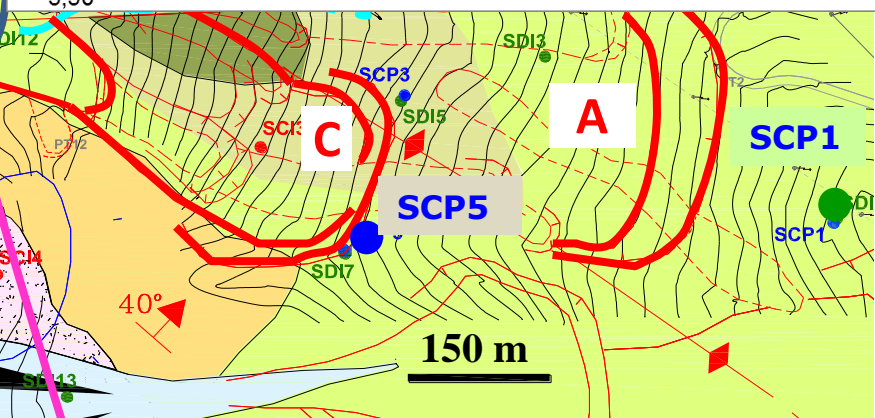
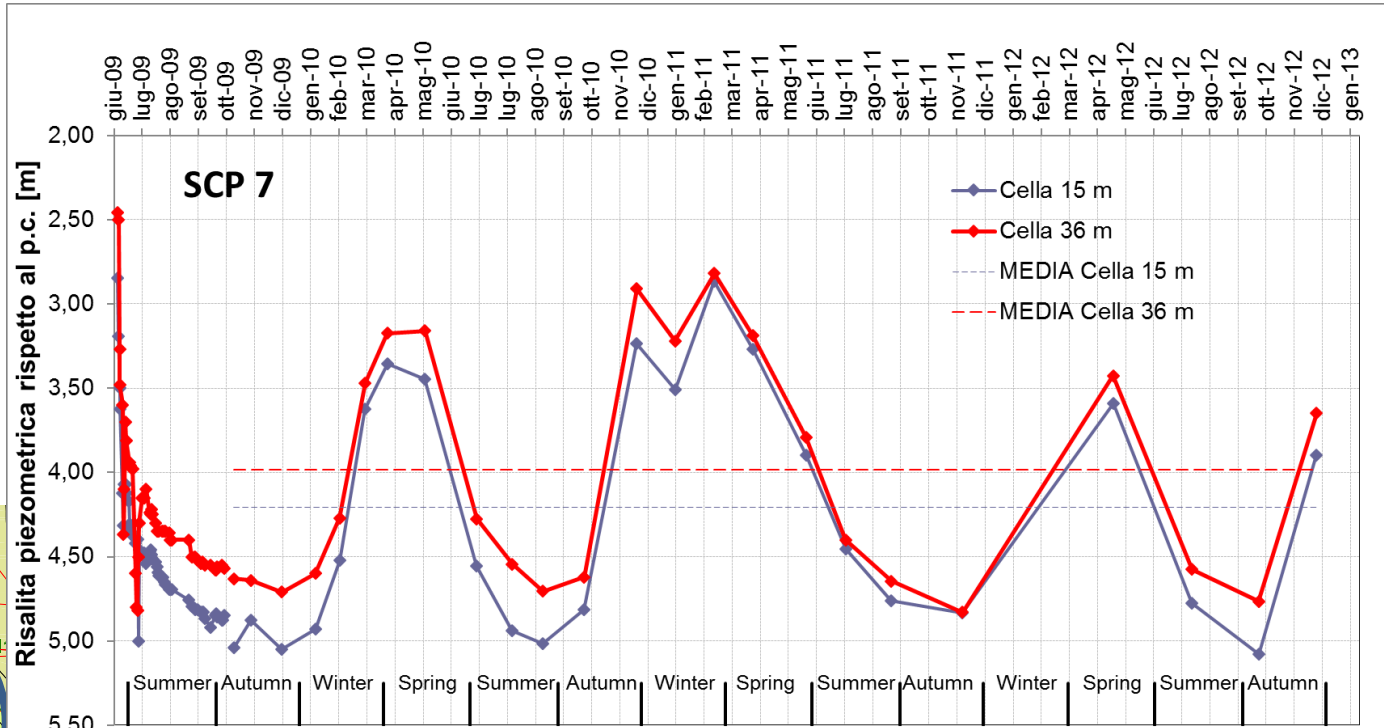
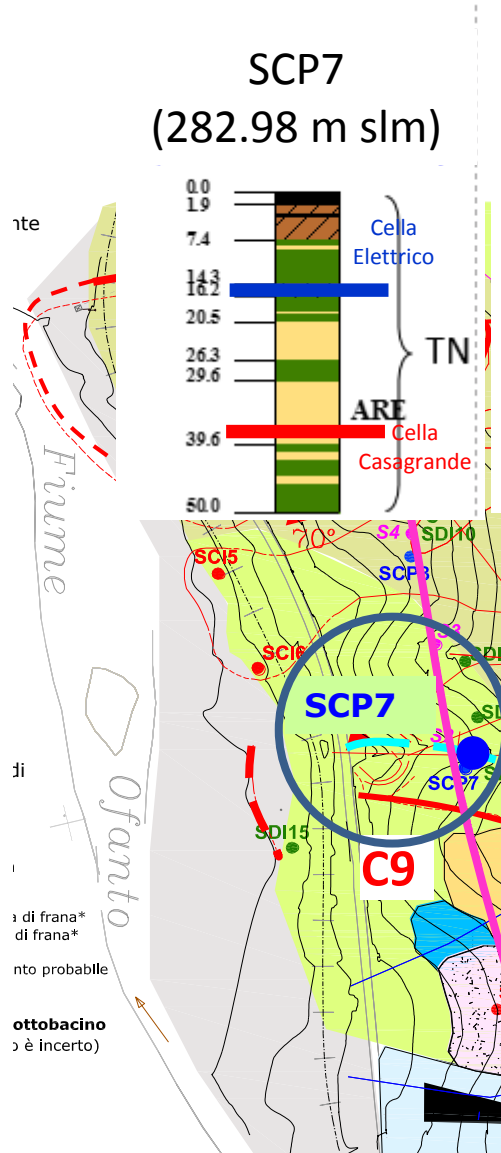


● Campione indisturbato  
■ Campione disturbato

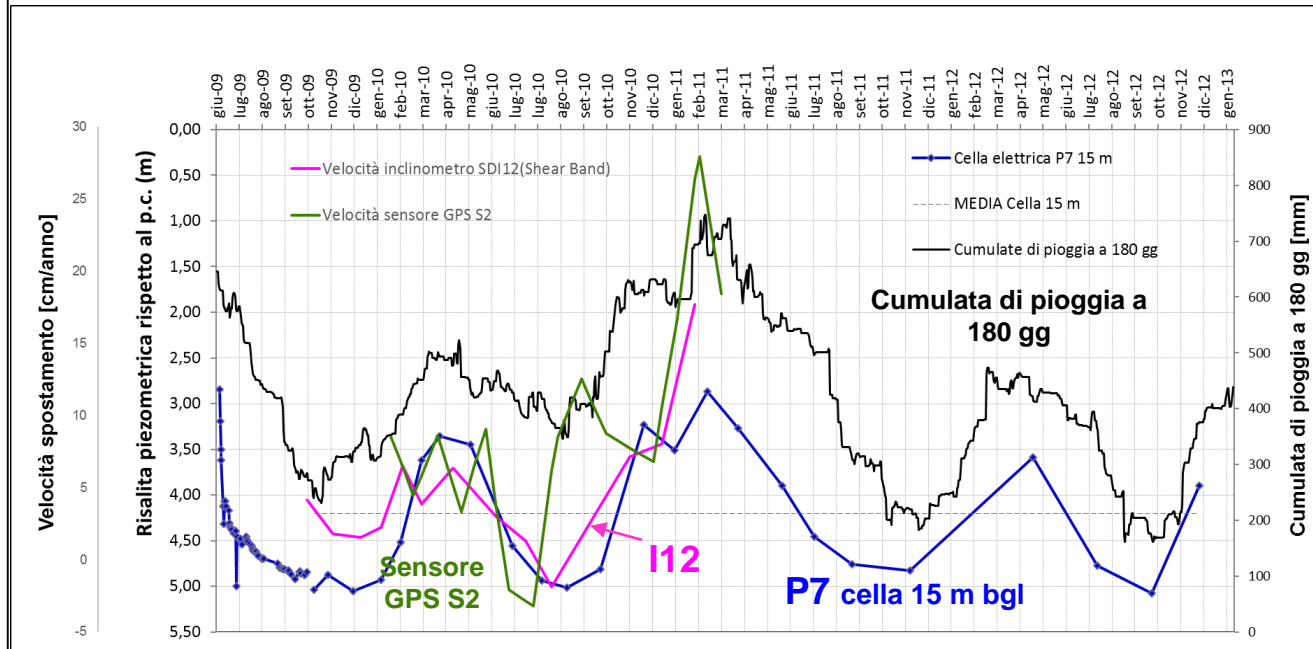
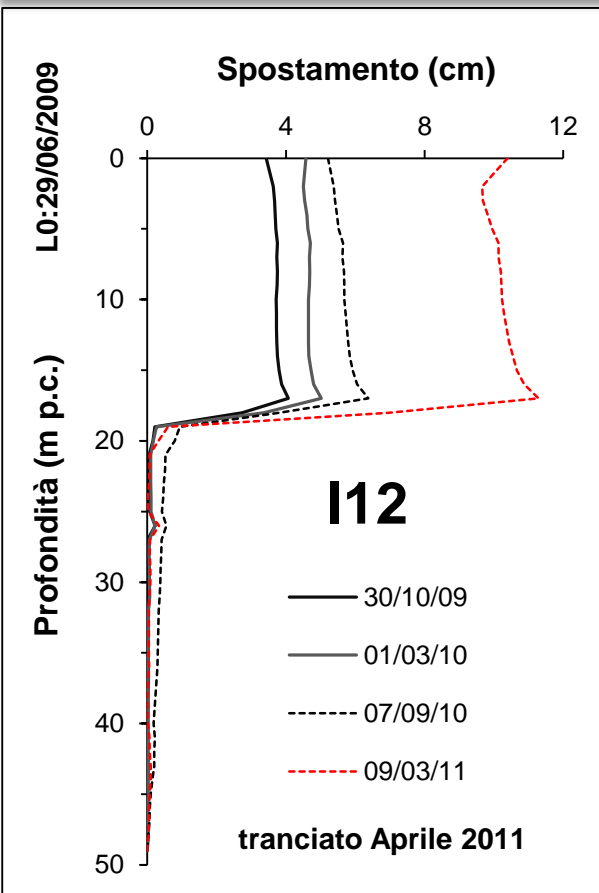
ottobacino (se è incerto)



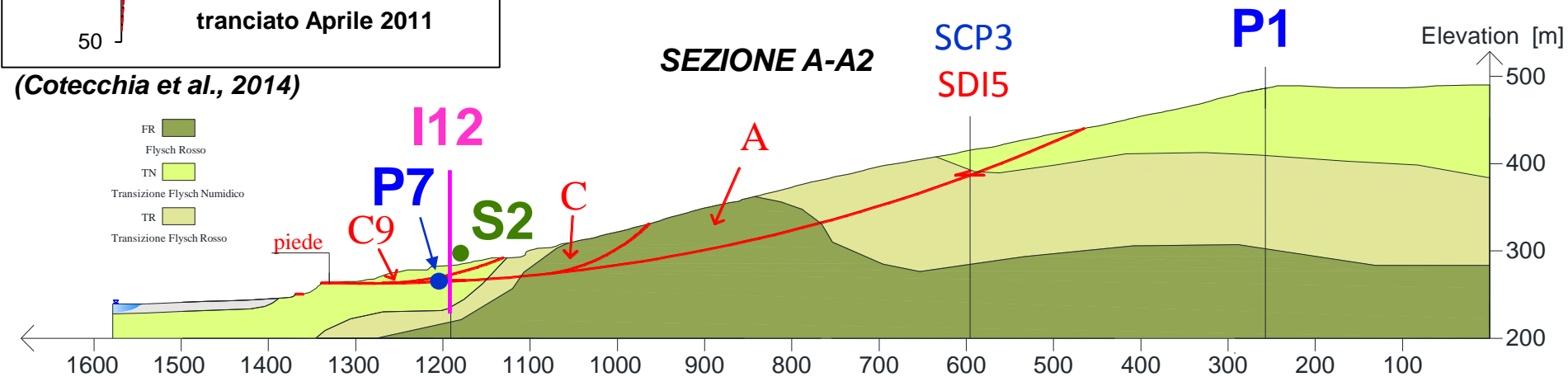
## Piezometrie – Piezometri Casagrande ed Elettrici



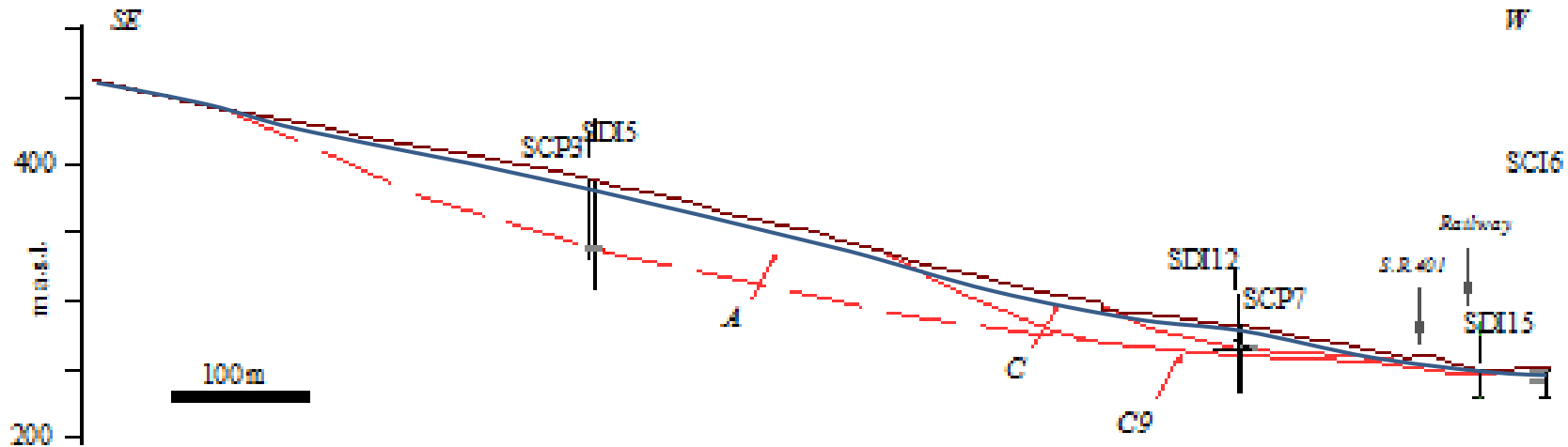




(Cotecchia et al., 2014)



## Back analysis con regime piezometrico invernale dell'equilibrio limite dei corpi C9, C ed A



$\phi'_m = 21^\circ$  Corpo A

$\phi'_m = 22^\circ$  Corpo C

$\phi'_m = 13^\circ$  Corpo C9

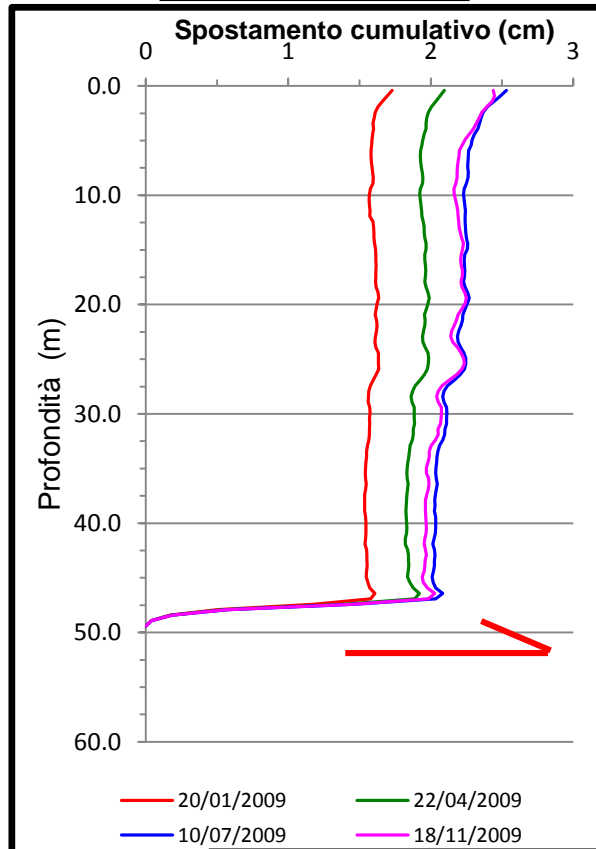
Resistenze  
Meccaniche in  
laboratorio

$c'=5 \text{ kPa}$   $\phi'=18^\circ-23^\circ$

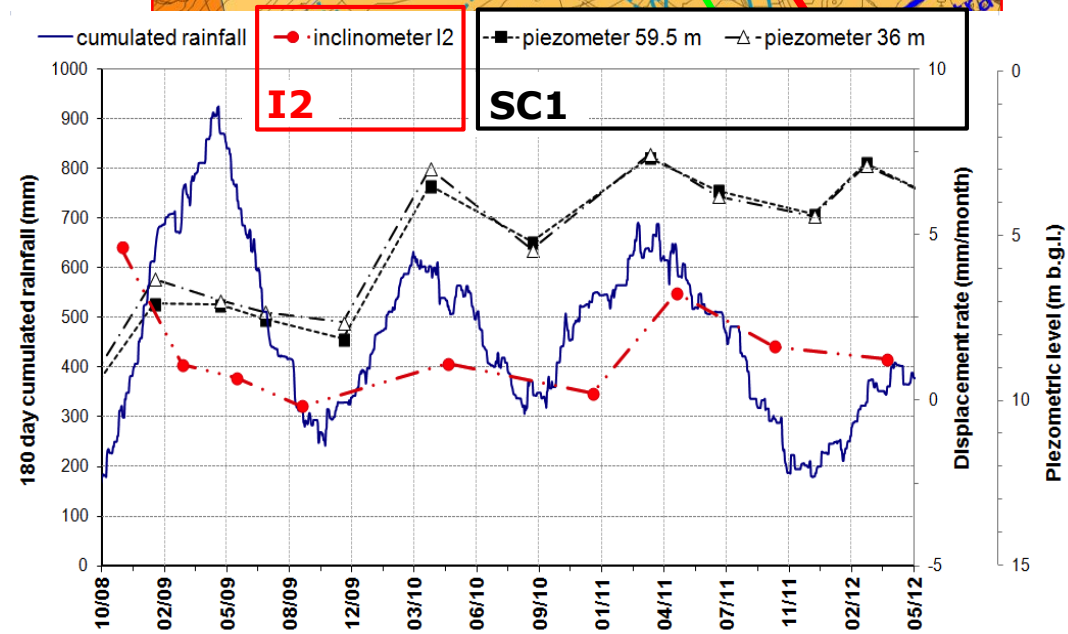
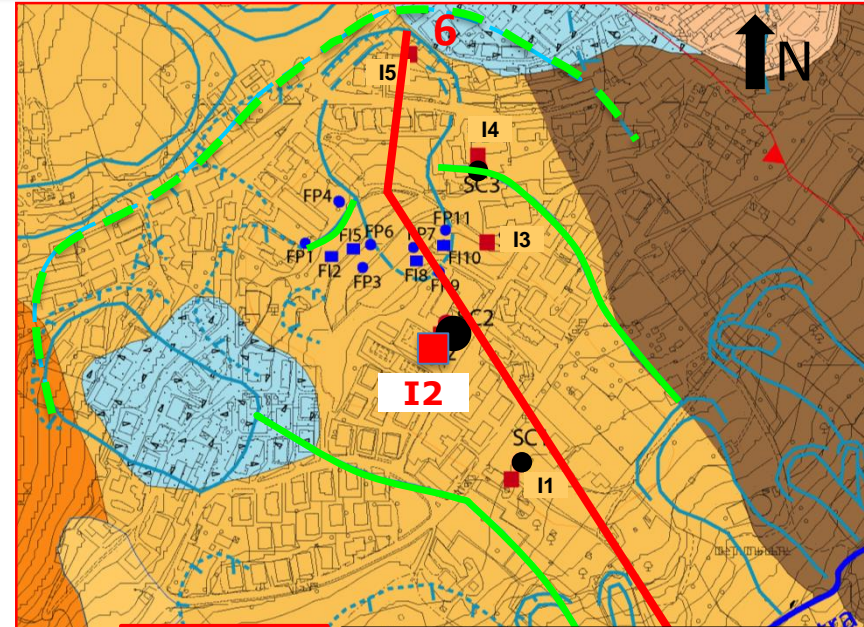
La resistenza mobilizzata ( $\phi'_m$ ) risulta essere compresa tra la condizione di picco e la condizione di post-picco per i corpi C ed A; il materiale coinvolto nel corpo C9 è più rimaneggiato

## Frana Pianello (Bovino)

Corpo A: **I2**

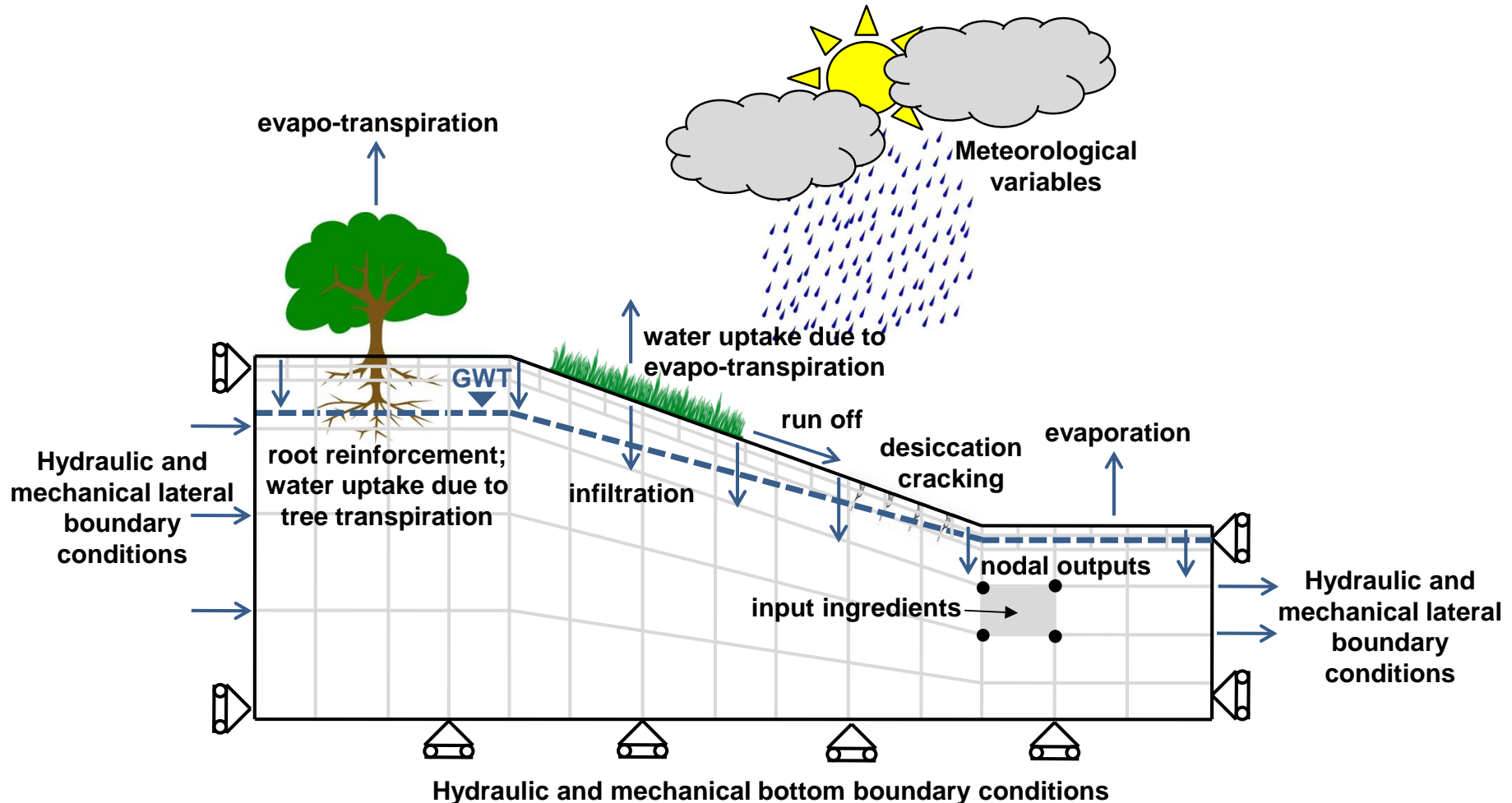


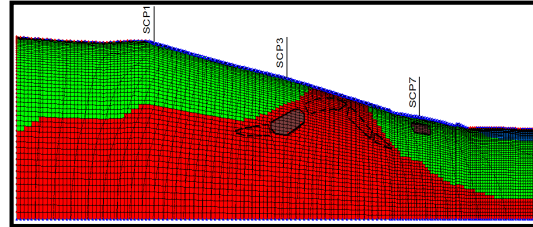
Banda di taglio intorno ai 47 m - movimento molto lento con  $v \approx 1.8$  cm/anno (L0-L2: circa 3 mm/mese)





## Il sistema pendio e le condizioni di bordo



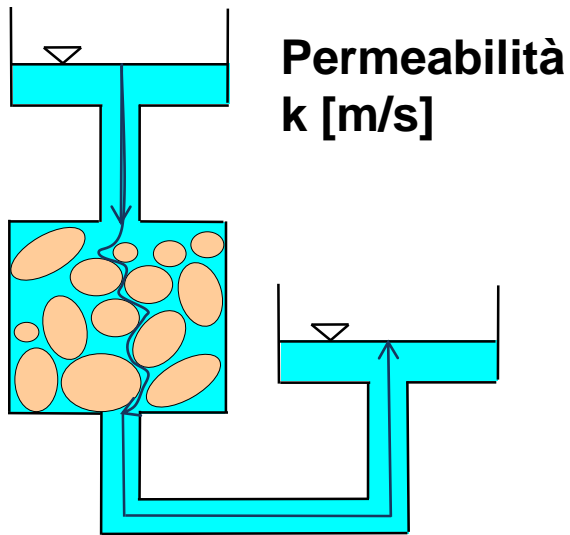


**Analisi numerica dei processi di filtrazione indotti dall'interazione  
pendio-atmosfera**



**Basata sulla caratterizzazione idraulica dei materiali coinvolti nei processi  
di frana**

## Caratterizzazione idraulica argille fessurate, in laboratorio



Permeabilità  
 $k$  [m/s]

$k = 10^{-9}$  m/sec  
= 3 cm/anno

(Darcy, 1856)

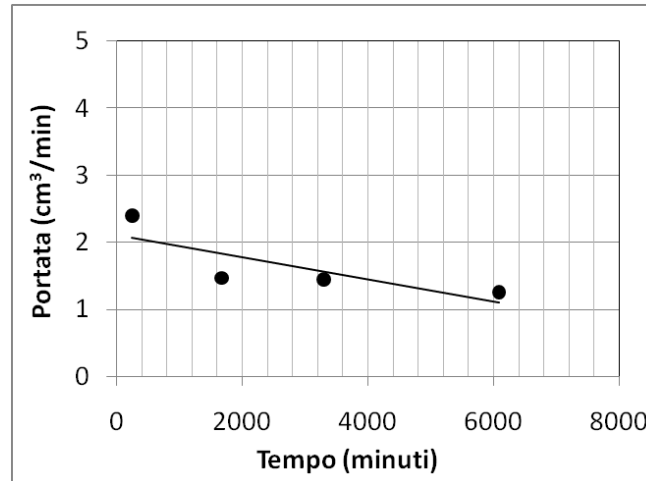




## Caratterizzazione idraulica argille fessurate, in situ



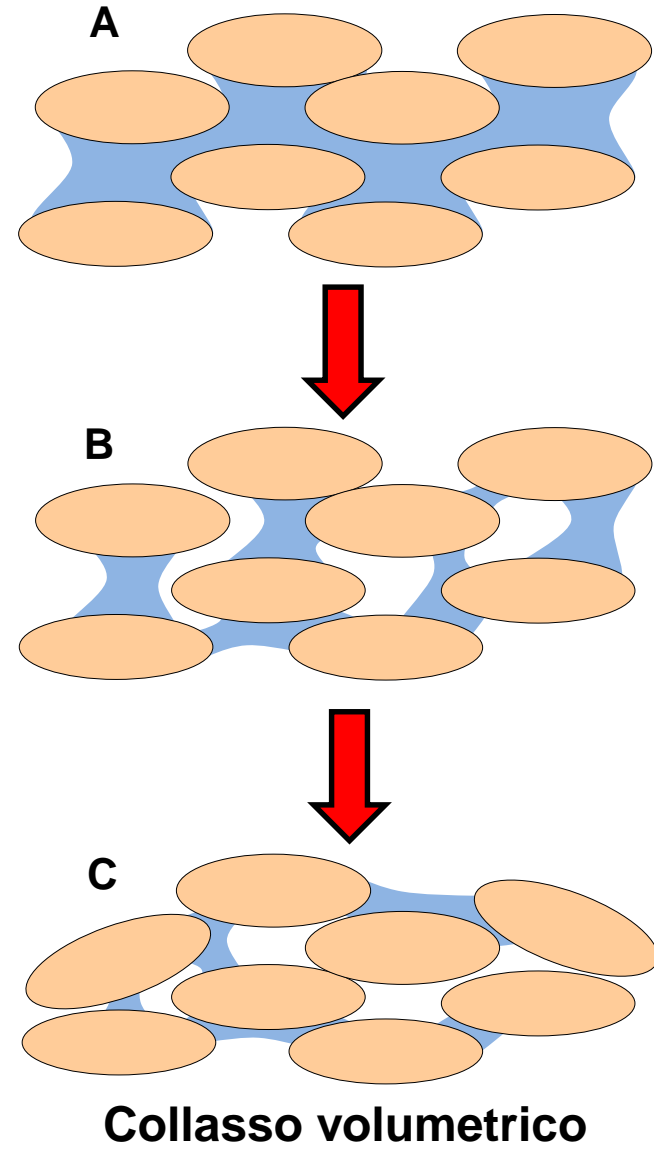
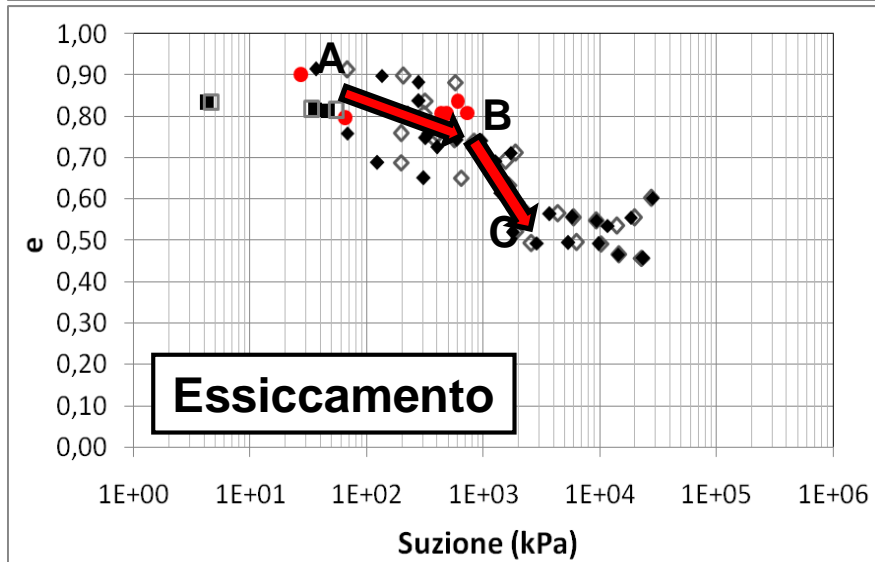
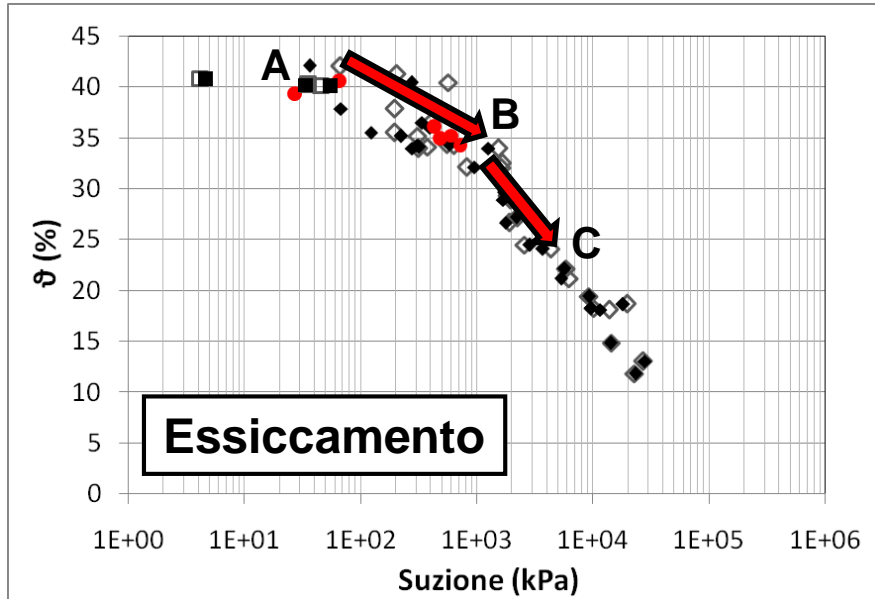
### Prova di permeabilità a carico costante



**$k = 6 \cdot 10^{-9} \text{ m/sec}$**

*(Cotecchia et al., 2014)*  
*(Pedone, 2014)*

## Caratterizzazione idraulica argille fessurate parzialmente sature



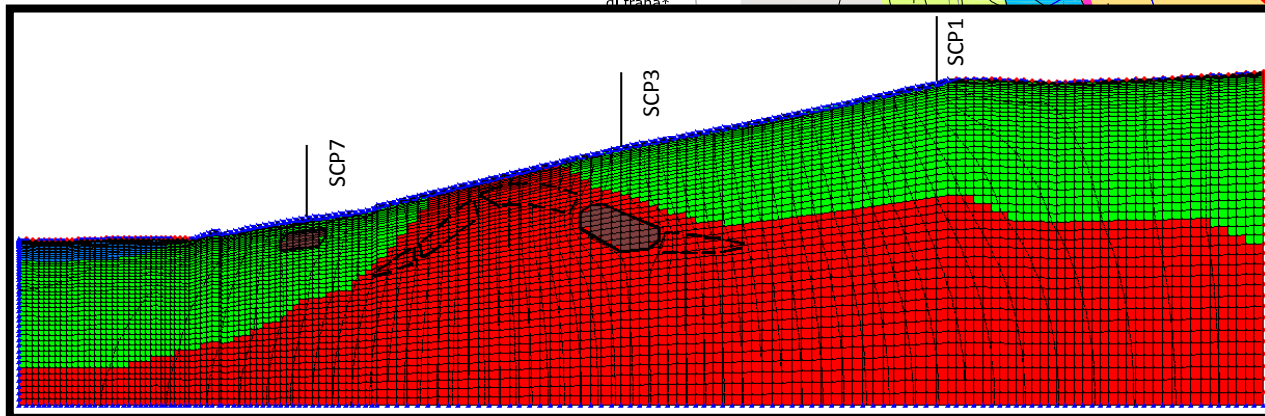
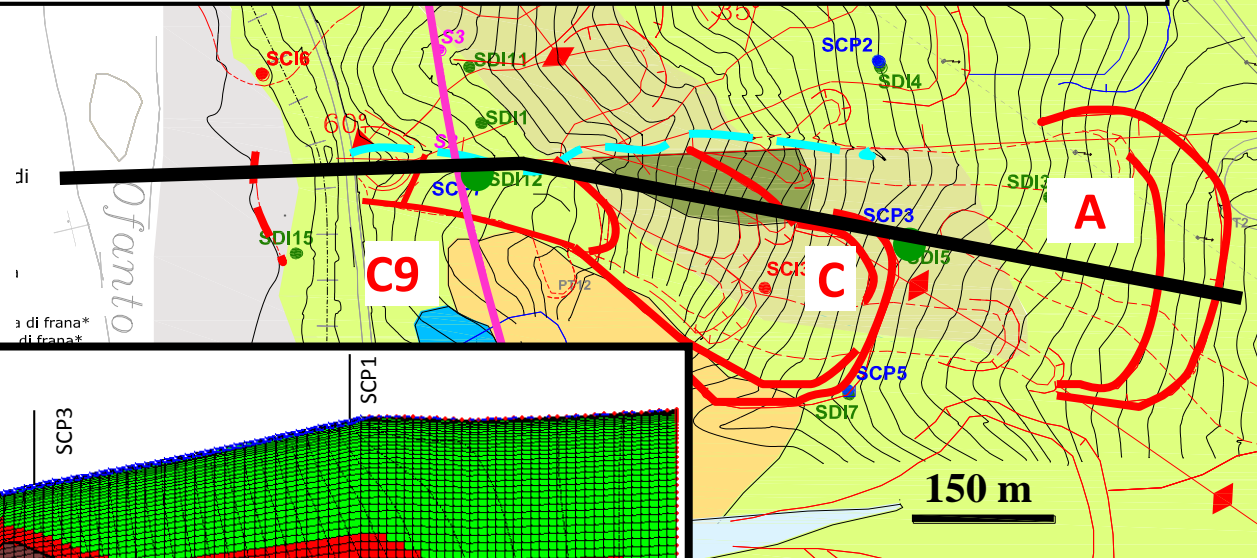
## Analisi numerica dei processi di filtrazione

### Equazione di Richards (1931)

$$\frac{\partial}{\partial z} \left( k_z(h) \frac{\partial h}{\partial z} \right) + \frac{\partial}{\partial x} \left( k_x(h) \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y(h) \frac{\partial h}{\partial y} \right) = \frac{\partial \theta_w(h)}{\partial t}$$

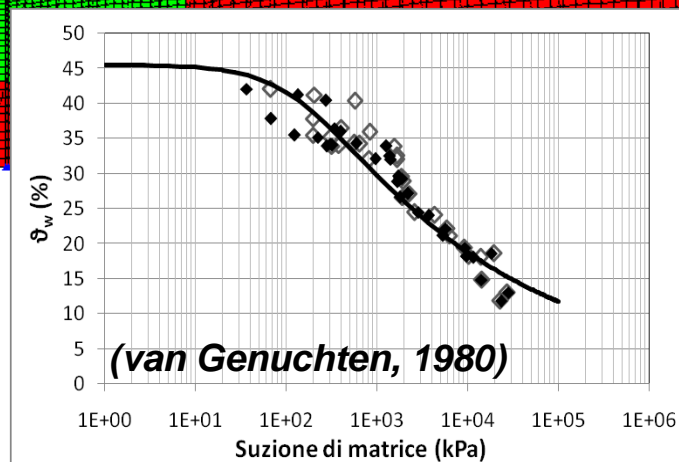
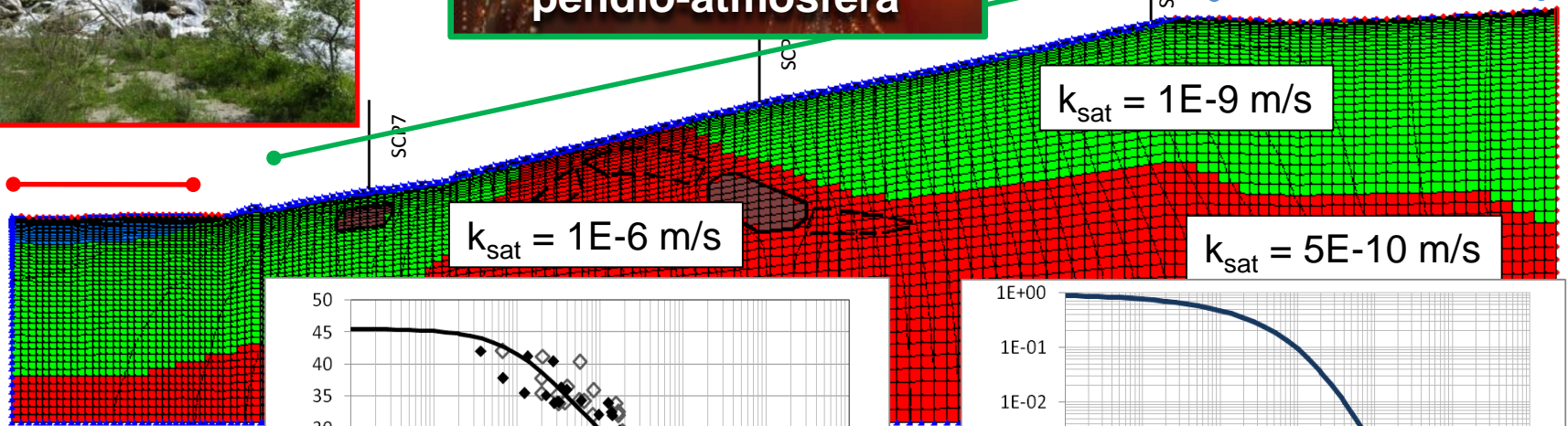
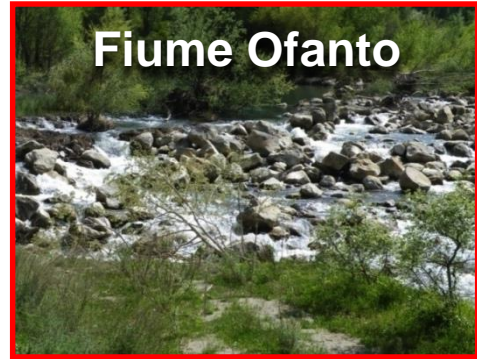
Curva di conducibilità  $k(s)$

Curva di ritenzione  $\theta(s)$

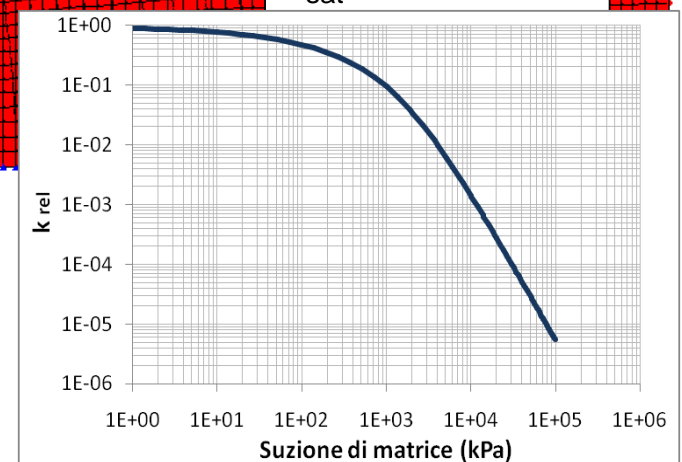




## Analisi numerica dei processi di filtrazione

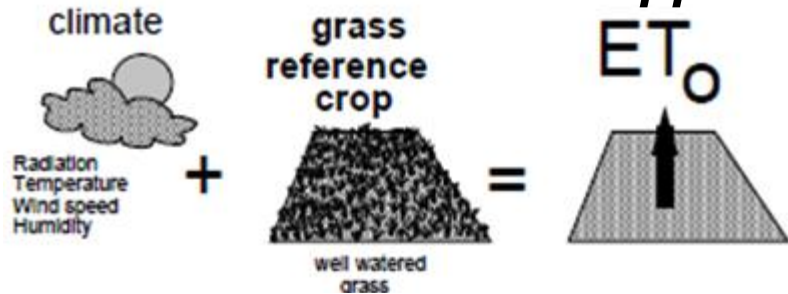


Curva di ritenzione



Curva di conducibilità

## Metodo FAO Penman-Monteith Doppio Coefficiente Colturale



$ET_0$   
DI RIFERIMENTO



"A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of  $70 \text{ s m}^{-1}$  and an albedo of 0.23."

IN CONDIZIONI STANDARD  
(POTENZIALE)

$$E_P = K_E \times ET_0$$

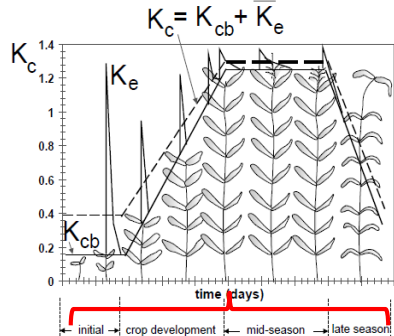
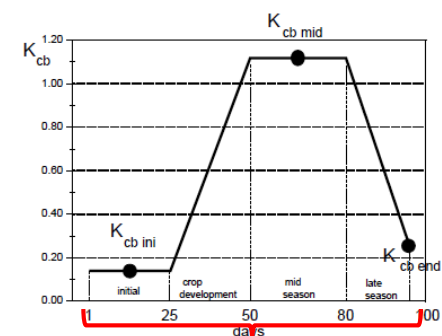
$$T_P = K_{CB} \times ET_0$$



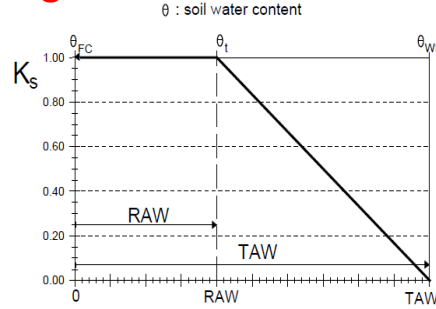
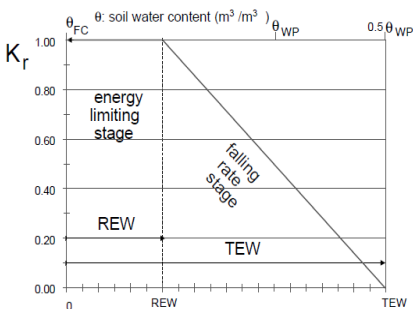
IN CONDIZIONI NON STANDARD  
(REALE)

$$E_R = K_R \times E_P$$

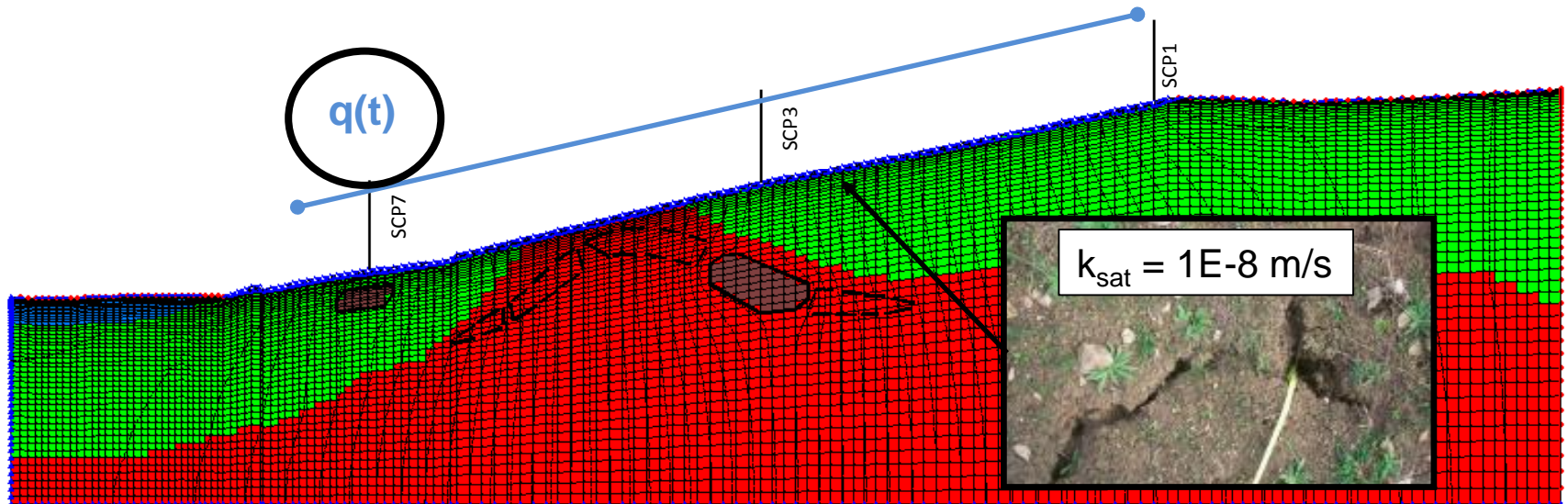
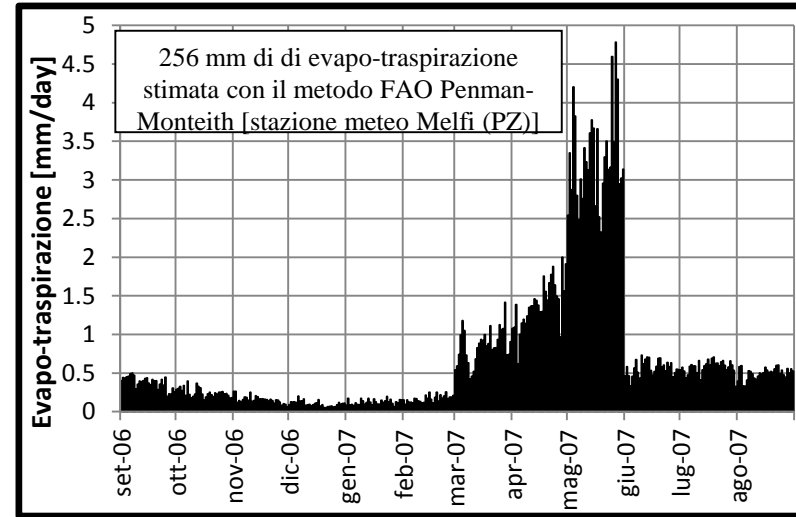
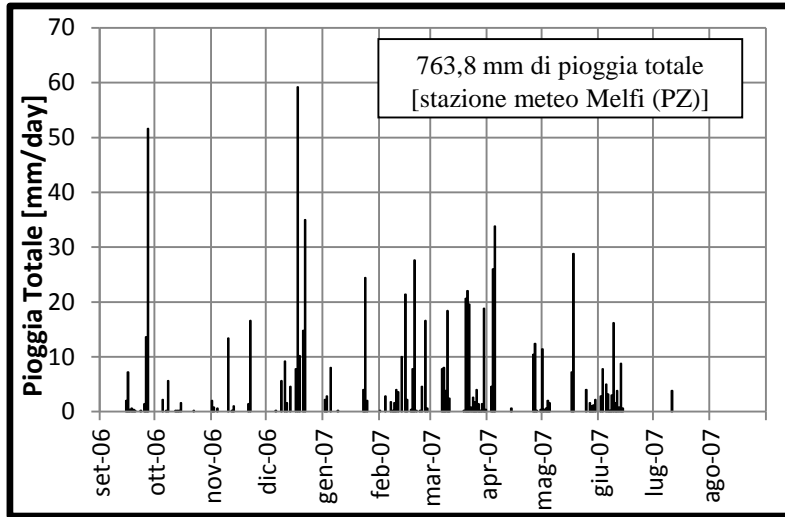
$$T_R = K_S \times T_P$$



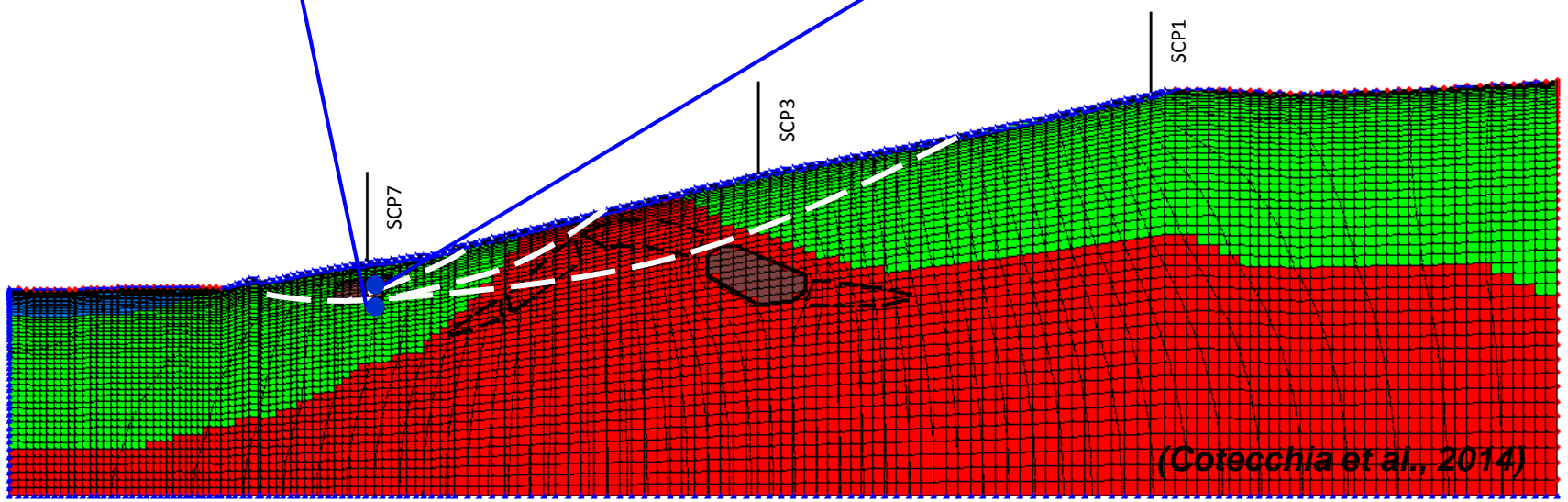
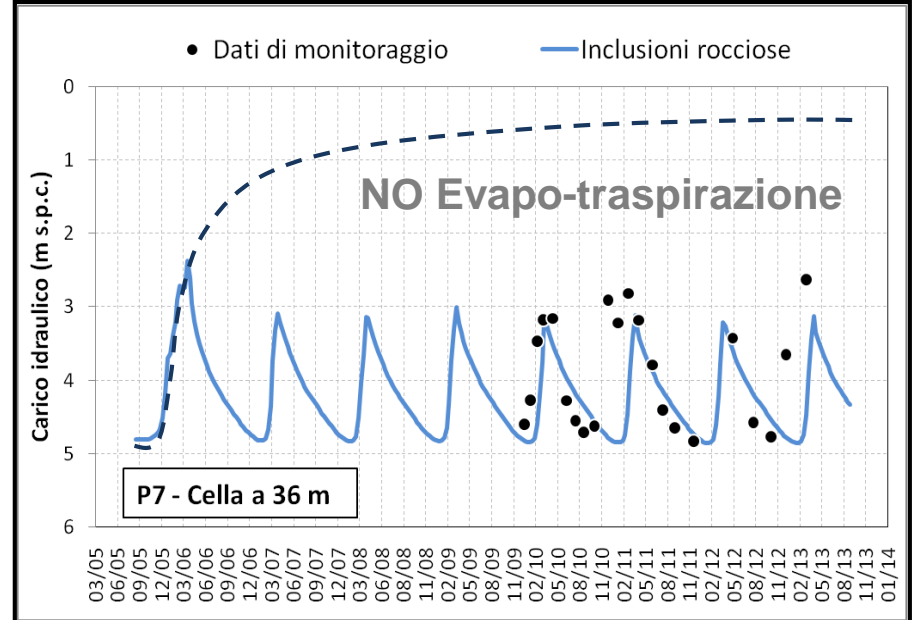
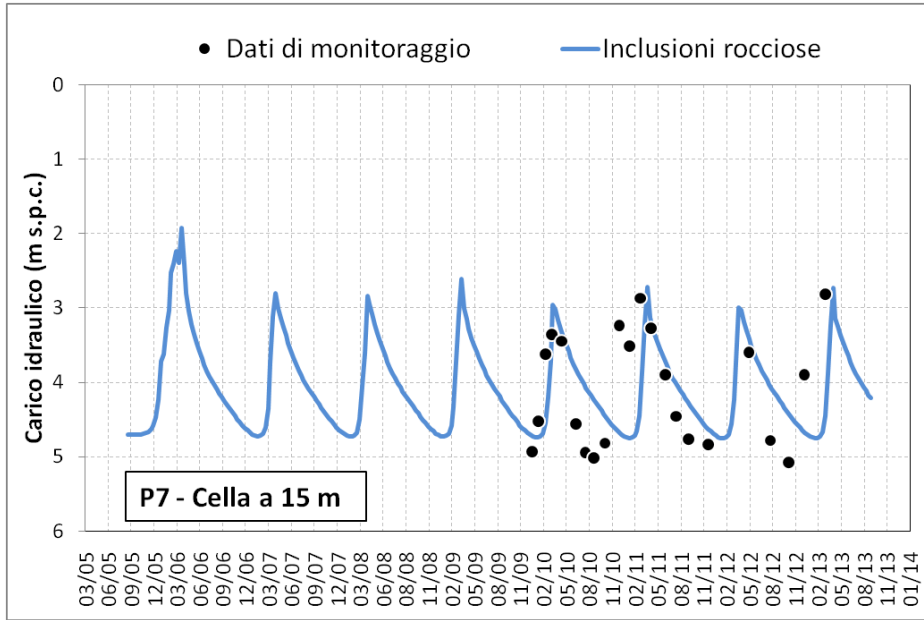
Ciclo vegetativo

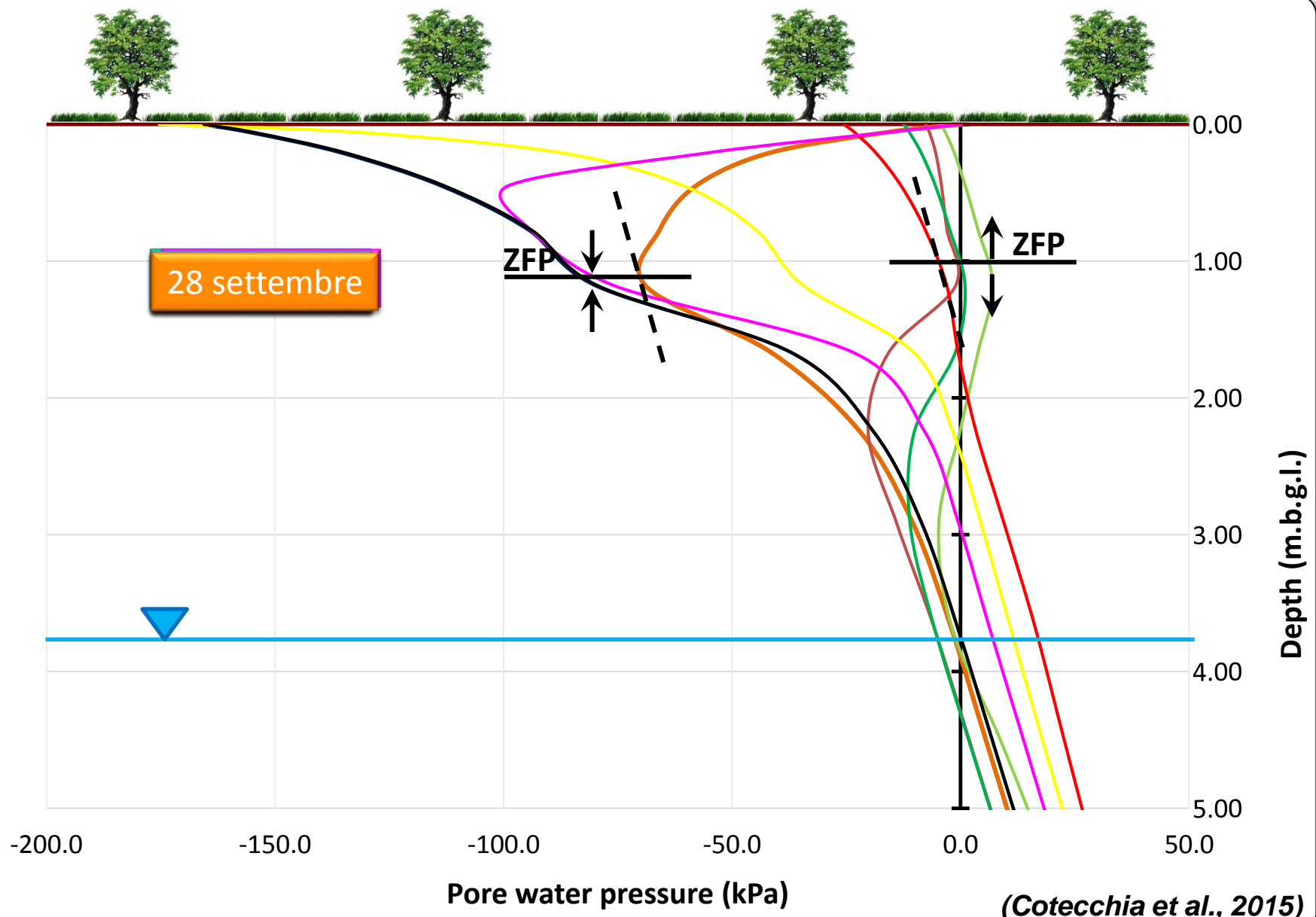


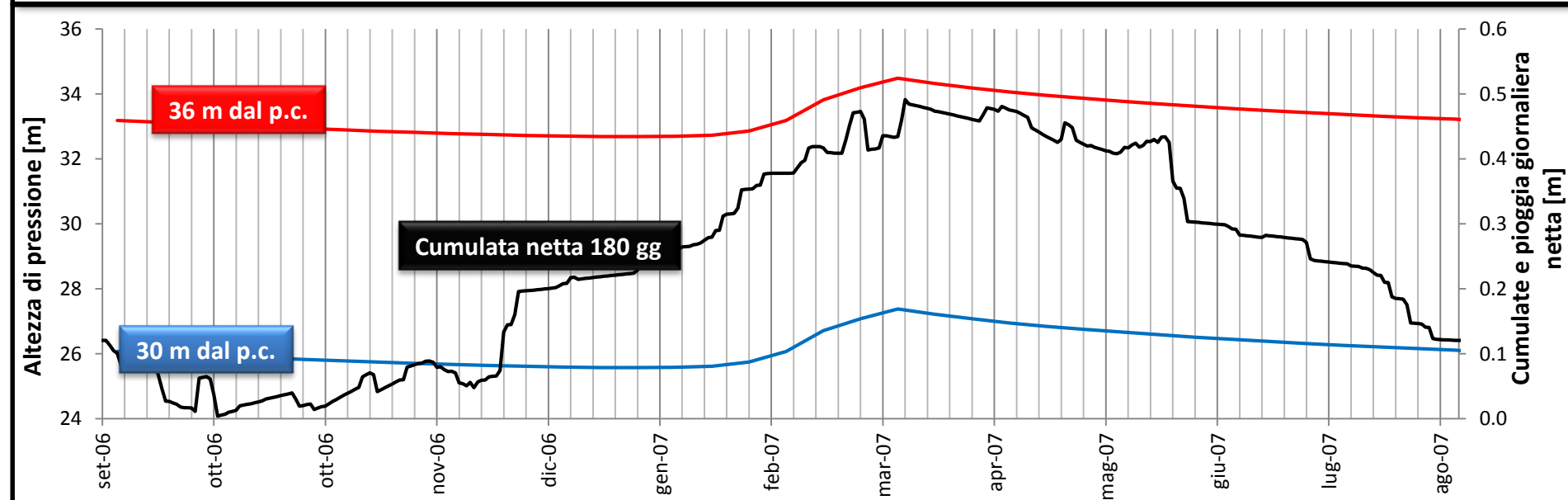
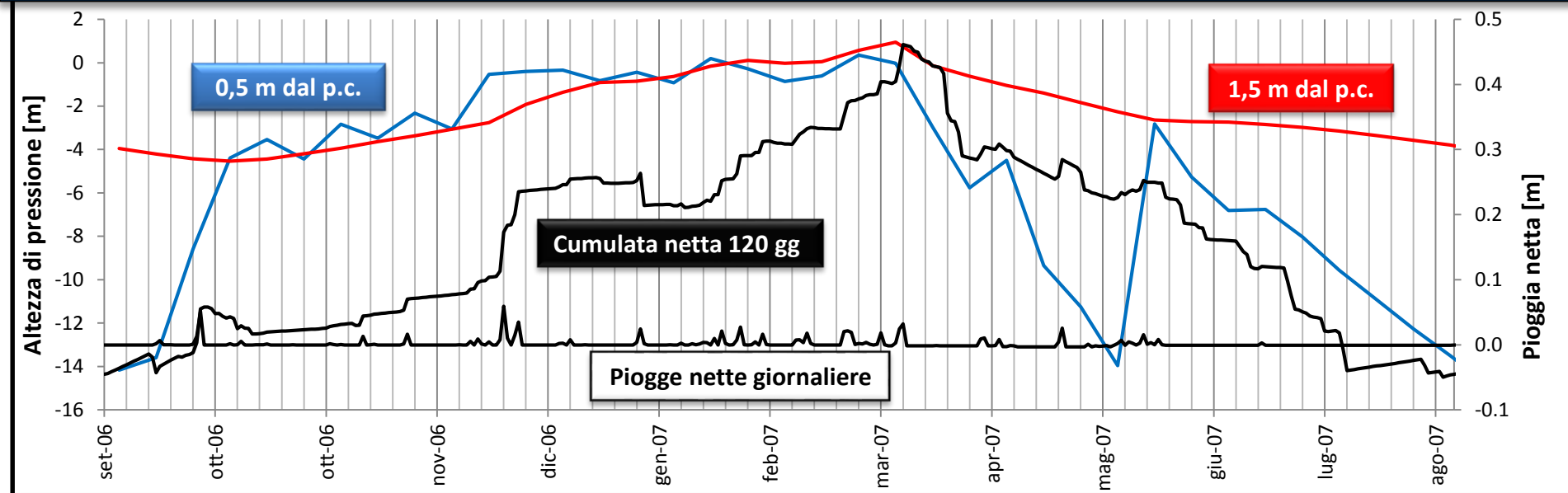
## Effetto dell'interazione pendio-atmosfera Filtrazione transitoria (Codice FEM Seep/W)







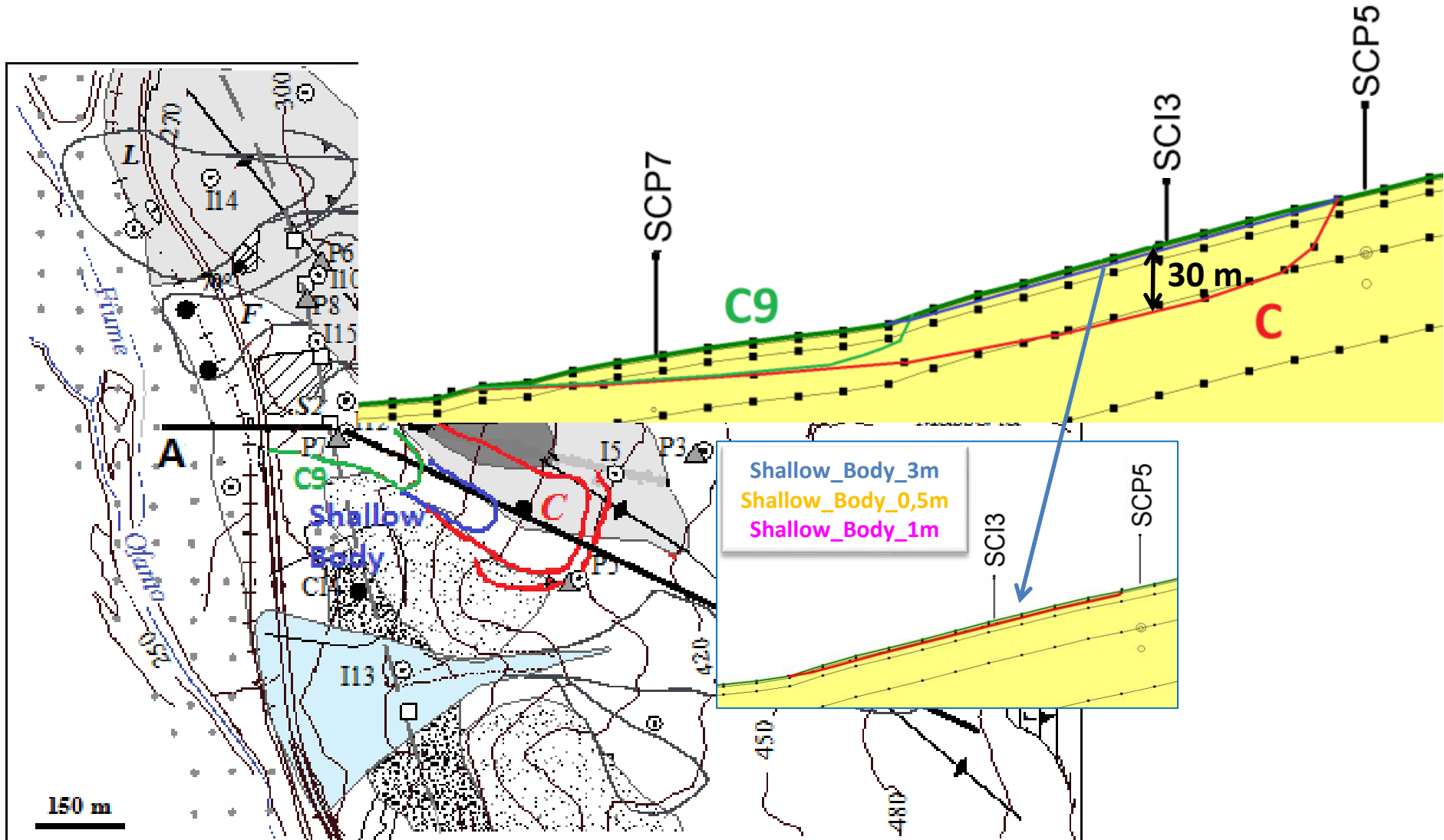


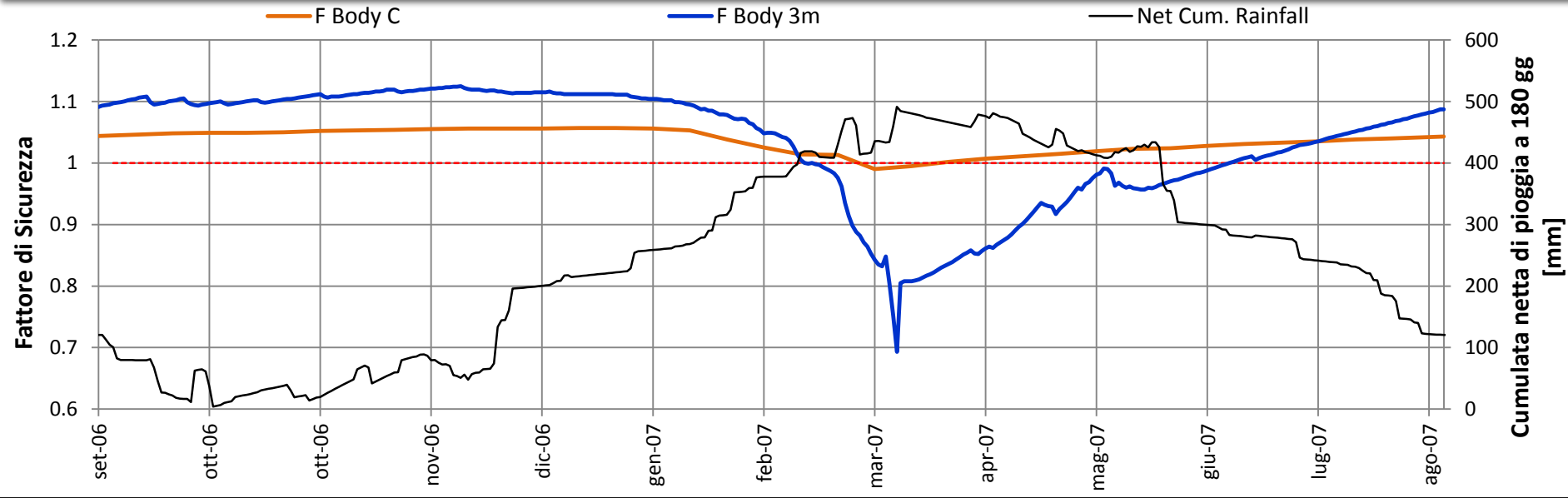
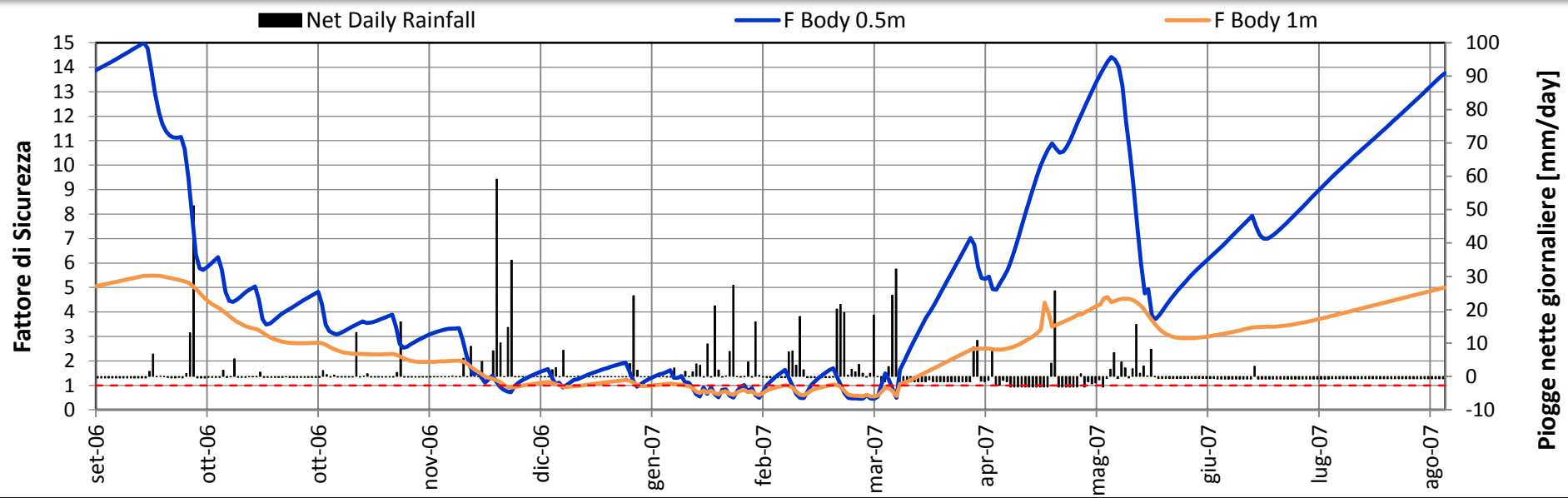




Metodo di analisi della stabilità:  
EQUILIBRIO LIMITE (LEM)

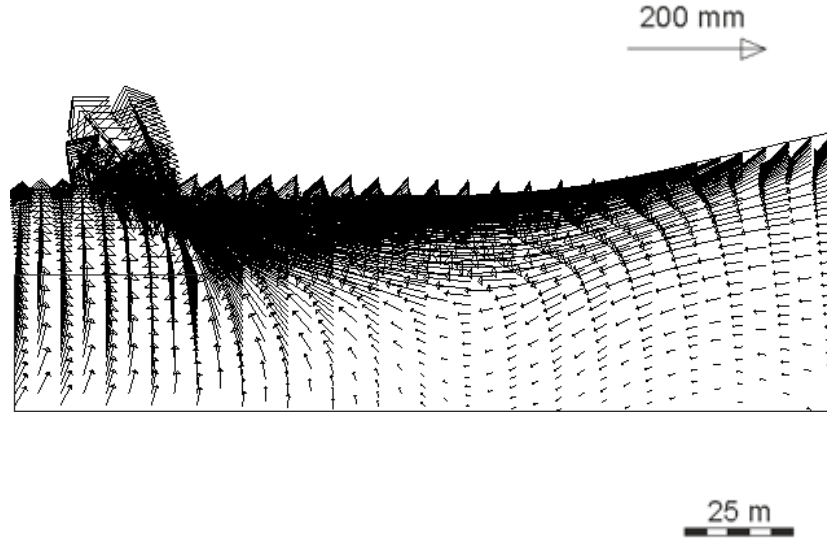
- In zona insatura (sopra falda):  $\tau_f = c' + (\sigma - u) \operatorname{tg} \phi' - s \operatorname{tg} \phi_b$
- In zona satura (sotto falda):  $\tau_f = c' + (\sigma - u) \operatorname{tg} \phi'$



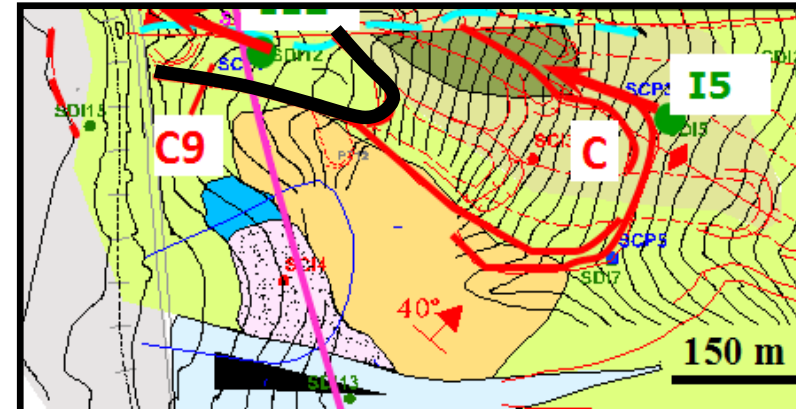


## Analisi idro-meccanica totalmente accoppiata

(Pedone, PhD Thesis 2014)  
(Pedone et al., in prep.)



**Meccanismo di prima rottura, mediamente profondo (~15 m)**



CONCLUDENDO....

Nei pendii dell'Appennino Meridionale sede di Flisch argillosi, le cui argille sono indebolite dalla fessurazione, **l'interazione pendio-atmosfera** è causa ricorrente di attività franosa dalle basse alle grandi profondità. Questo risultato dovrebbe indirizzare le strategie di allerta e di mitigazione del rischio da frana in questi contesti geo-idro-meccanici